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ABSTRACT

A hierarchical approach for the determination of a manpower and machinery configuration for a naval tender machine shop is presented. The application of numerically controlled machine technology is stressed. A mixed integer programming model is developed to support aggregate decisions regarding machinery and manpower allocations. The job shop performance under the suggested aggregate characteristics is tested by a detailed simulation model. An iterative procedure links both models to ensure satisfactory overall performance. Typical naval tender machine shop workload is used in the model implementation.

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CHAPTER I

INTRODUCTION

I. A. The Nature of Naval Tender Operations

It is the purpose of this thesis to develop an analytical method to examine the application of numerically controlled machine technology to a naval tender machine shop. Although the purpose as stated is quite specific, the naval tender machine shop will be seen to be a subset of the classical job shop, so that extension to other job shop contents may be possible. It is most important to understand the environment in which this floating and movable job shop operates; we shall see that the demand and constraint characteristics of the naval tender machine shop differ markedly from those of the traditional job shop. Prior to delving in at this very specific level, however, let us examine the role of the naval tender in the context of the overall Navy logistics and ship maintenance hierarchies: this macroscopic view will define certain boundary conditions within which the tender machine shop must operate.

Ship maintenance is divided among three distinct levels: these are organizational (the ship itself), intermediate (tenders and repair ships), and depot (naval and civilian shipyards). Maintenance at the organizational level refers to those functions normally performed by the ship force personnel in daily support of its operations. Maintenance at the intermediate level generally includes the following: 1) repair and testing of equipment and systems, which requires skills and/or equipment not available to the individual ship; and 2) approved alterations not within the capability of individual ship force personnel. Depot maintenance usually refers to the accomplishment of work during a regular overhaul (general repairs and alterations at a shipyard activity, normally scheduled in advance and in accordance

with an established time cycle -- e.g., sandblasting and painting of the underwater hull every thirty-six months) or a restricted availability (due to the scope of the work to be accomplished, the ship is rendered incapable of performing fully all assigned missions -- e.g., repair of battle damage, or drydocking to replace sonar elements at other than a scheduled time). The above description has been greatly simplified -- for example, a ship undergoing a regular overhaul will be accomplishing its own corrective and preventative maintenance, and have tender personnel aboard to provide technical assistance, while having various parts and equipments at the tender for repair, all simultaneously -- but perhaps it will aid in providing some structural and contextual information to the reader unfamiliar with the area.

Naval tenders and repair ships operate within different administrative and command contexts; for the purposes of this study, however, we shall not differentiate between these two types of ships, but shall refer to them in general as naval tenders. These naval tenders will typically tend from five to fifteen ships at one time. A typical operational scenario for a tender might include six months at a continental United States port, four weeks underway across either the Atlantic or Pacific, and six to nine months in one or two foreign ports, and then return to the continental United States. It is obvious that the tender performs an especially important function while it is deployed: if something fails, and it is beyond the capability of ship force personnel to repair and test, the tender may be the only source of assistance within several hundreds of miles. The primary consideration in tender effectiveness, then, must be quick and reliable response to the customer -- the fleet -- under various demand characteristics: it must be noted that there is no explicit cognizance of profit maximization, cost minimization, machinery and/or personnel utilization, etc., although less

expensive and more efficient ways of providing a quick and reliable response are certainly desired.

We shall assume for the remainder of this study that the simple structural relationship described above (organizational, intermediate, and depot levels of maintenance and logistical support) remains relatively static; some movement in relative proportions of total work to be accomplished is allowed (e.g., if the standard overhaul cycle is extended by twelve to eighteen months) but the existing structure is assumed to continue. Inherent in this assumption is that the naval tender remains an integral part of the fleet composition. Similarly, the decisions regarding economic order quantities for the various components of the fleet, and storage decisions around the globe, etc., we shall assume are exogenous to our examination, and relatively constant.

Having presented a brief and greatly simplified structural and contextual survey of the nature of naval tender operations, let us now present a generalized view of productive systems. This movement from the specific to the general has two purposes: 1) the reader familiar with previous production management studies can place the naval tender machine shop in a more familiar context; and 2) comparison with other types of productive systems may yield improved definition of the naval tender machine shop. Buffa [5] divides productive systems into four general areas of classification. The continuous inventory system is keyed to maintenance of inventory in readiness to meet varying demand patterns at either the consumer, distribution, production, or raw material supply points; examples include individual retail stores and factory warehouses. The continuous high volume production-inventory system produces such items as light bulbs or facial tissue. The intermittent system is keyed to holding facilities and/or manpower in readi-

ness to meet demands dependent upon design, style, or technological requirements. The job shop falls within this latter classification; a further subdivision is possible into open systems which are open to custom orders, and closed systems which are "captives" of a larger enterprise. The last major classification refers to large-scale one-time projects, such as the construction of an oil refinery. Most productive systems will share characteristics of at least two systems, but one classification will most probably dominate; nonetheless, the above classification system of Buffa does provide a general and useful framework.

With reference to the above framework, the naval tender machine shop most closely fits into the intermittent, open job shop classification wherein a supply of equipment and trained mechanics, the combination of which can perform wide varieties of operations, is held in readiness to meet a widely fluctuating demand for repair work from the fleet of ships for which it is responsible. Since the naval tender machine shop fulfills primarily a response function, i.e. responding to equipment failures, there is very little production for inventory. It should be noted as well that there are legislative constraints pertaining to government production of parts, which also discourage production for inventory. Further, since demand is mainly responsive to failures, consideration of uncertainty is of paramount importance. Although the shore-based civilian job shop can turn down excess work and the customer can approach another job shop, many times the naval tender machine shop will be the sole resource of its type available in an area covering thousands of square miles. Therefore, prediction of an upper level of workload at any one time on the machine shop is most difficult; and of course, allocation of this work among the various machine groups and to the proper skill class worker is just as difficult to predict.

I. B. The Decisions Required for a Naval Tender Machine Shop -- An Overview

In the previous section we provided an introduction to the naval tender, and examined the various structural, contextual, and operational environments within which it operates. We are concerned, however, with but a portion of the naval tender -- the machine shop. In Chapter II we shall describe in detail the naval tender machine shop; and we shall briefly review the nature of numerically controlled machinery and examine potential areas of application within the tender machine shop. It is sufficient in this introductory chapter, however, to consider the naval tender machine shop to be a specialized type of the classical job shop; we have already seen that the job shop is a subset of production systems in general. We can therefore introduce many of the decisions required for a naval tender machine shop in the context of studies pertaining to general production systems.

Let us first categorize the tender machine shop decisions using the familiar taxonomy of Anthony[1] regarding strategic planning, tactical planning, and operational control. Anthony defines strategic planning as the "process of deciding on objectives of the organization, on changes in these objectives, on the resources used to attain these objectives, and on the policies that are to govern the acquisition, use, and disposition of these resources." Given that the objectives, and various changes thereto, of the naval tender machine shop are exogenously supplied, then the strategic decisions remaining pertain to the onboard facilities and capacity, including major capital investments for equipments to meet existing or forecasted demand. It is obvious that a long planning horizon is implied in such decisions; further, these strategic planning decisions set certain constraints and boundary values on the shorter term operation of the system.

The output of the strategic planning decision process, then, is deter-

mination of physical/equipment facilities. Management control (tactical planning) is then required so that the resources are used effectively and efficiently in satisfying the tender's objectives. The decisions made at this level involve aggregated information; therefore, operational control is required to assure that the day-to-day operations of the tender machine shop are accomplished effectively and efficiently.

A second overview of the hierarchical set of decisions required in a production facility has been presented by Holstein[17]. With minor revision, Shwimer[29] has applied Holstein's decision set to a job shop. He cites the following sets of decisions:

-- long-term capacity planning (horizon of one or more years) which involves the major adjustments of plant capacity to match projected requirements;

-- master scheduling or medium-term production planning (horizon of one or more months) which matches the available capacity to individual products and major orders as well as making minor adjustments to the available productive capacity (e.g., work force size changes, use of overtime);

-- short-term scheduling (horizon of one or more weeks) which includes the more detailed plans which ensure that the delivery commitments represented by the master schedule are met; and

-- dispatching and shop control (horizon measured in minutes or hours) which includes the problems of detailed information gathering (e.g., the current status of job XYZ) and the immediate decisions regarding what task a particular worker does next.

All of the decisions discussed in general above must be made subject to various constraints. Some of these constraints are exogenously supplied; other constraints result from decisions at one level, and markedly affect those at lower levels; it is important to note, however, that decisions made at the lower levels (i.e., at shorter time horizon points) may in fact be such that they should be examined for their potential impact on higher level decisions -- this point will become clearer later in the development of this thesis when feedback is employed in the model solution.

I. C. The Plan of this Thesis

In this chapter we have examined the nature of naval tender operations and have introduced the various structural, contextual, and operational environments within which the naval tender must operate; we have also presented a general framework within which the naval tender machine shop, and the decisions required for its operation, can be analyzed. We shall proceed to develop a model for examining a proposed facilities expansion/capital expenditure problem concerned with applying numerically controlled machinery to the naval tender machine shop.

In the next chapter, we shall attempt to define more fully the naval tender machine shop and the characteristics of numerically controlled machine tools, and will end with a verbal description of a total model. A more rigorous total model (i.e., in mathematical symbols) is not generated for three reasons: 1) present computer and methodological capabilities do not permit solution of such a large integrated/detailed production model; 2) far more importantly, a single mathematical model does not provide sufficient cognizance to the distinct characteristics of the time horizons and scopes of the various decisions; and 3) a partitioned, hierarchical model facilitates management interaction at the various levels.

In the third chapter the total model will be decomposed into two submodels; the important dimension in the decomposition will be the time horizon for the decision. One submodel, called the aggregate model, is readily amenable to optimal solution using mixed-integer linear programming techniques and codes. The other submodel, called the detailed model, is not amenable to presently existing computer code solution, and therefore a simulation procedure is recommended.

In the fourth chapter, experimentation with the aggregate model and the

detailed simulation is discussed. Methods of determining coefficients for the objective function and various constraints are described. Generation of workload for input is discussed.

In the fifth chapter, a summary of the thesis is provided; additionally, suggestions for model implementation and a possible system configuration are presented.

CHAPTER II

GENERATION OF A TOTAL MODEL

II. A. The Naval Tender Machine Shop

The first chapter contained a general introductory discussion of the naval tender machine shop. In this chapter, we shall first take a closer look at the naval tender machine shop; then we shall examine the nature of numerically controlled machinery and see potential areas of application within the tender machine shop; in order to develop a model which will examine the impact of numerically controlled machinery on the tender machine shop, a listing of assumptions will be necessary; and finally in this chapter, a total model will be presented.

The principal functions of a naval tender machine shop are to repair pumps, valves, and related and similar mechanical equipment; to serve assist functions for other tender shops; to manufacture machinery replacement items; and to accomplish grinding and engraving work. The typical modern naval tender machine shop will contain milling machines, drill presses, grinders, engine lathes, a furnace, a dip tank, band saws, shapers, turret lathes, boring mills, a disintegrator, an Arbor press, and various other equipment. The shop is supervised by three chief petty officers and there are several petty officers first, second, and third class, as well as a large number of "non-rated" machinery repairmen.

For the remainder of this thesis, the term "naval tender machine shop" will be utilized to describe the above typical shop, without consideration of the engraving and grinding sections. This assumption is considered appropriate for three reasons: 1) there is virtually no cross-training between either the grinding section or the engraving section and the remainder will have no effect on either of these two sections; 2) although numerical con-

trol may have some application to engraving work, we shall not consider applying numerically controlled machinery in this area at this time -- note, however, that the proposed approach of this thesis could be applied in some later study to the engraving section after generation of appropriate data; and 3) simplification to reduce the scope of our study, without reducing application of the results.

Therefore, the naval tender machine shop which we shall consider in this study will have the following initial configuration:

Heavy section

-- milling machines (plain and universal);

-- drill presses (standard and radial);

-- engine lathe (Monarch);

-- band saws;

-- vertical turret lathes;

-- horizontal boring mill; and

-- gap lathe; and

Light section

-- lathes (American and Springfield, 16" and 20"; and Cincinnati,13");

-- drill presses (Cleereman);

-- horizontal turret lathe; and

-- Arbor press

II. B. The Nature of Numerically Controlled Machine Tools

In previous sections of this thesis, the nature of naval tender operations has been introduced and we have presented a survey of the naval tender machine shop in its present configuration. Let us now examine the nature of numerically controlled machine tools and understand why their application to the naval tender machine shop may be desirable.

The Electronics Industries Association [11] provides the following definition of numerical control: "A system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data." A less restrictive description is that numerical control provides for the automatic operation of machinery, using as an input discrete numerical data and instructions stored on an appropriate medium such as punched or magnetized tape; the motions and operations of numerically controlled machine tools are therefore controlled primarily not by the operator but by an electronic director which interprets coded instructions and directs a corresponding series of motions on the machine.

Development of numerical control was begun in 1948; in 1949, MIT was brought into the effort. Early numerical control machines were an application of the player-piano principle to conventional machinery. Present types of numerical control machine tools are highly sophisticated, frequently combining the operations of several conventional machines: the numerically controlled machining center, for example, performs milling, drilling, boring, and cutting operations which until recently were frequently accomplished on separate conventional machines.

Several excellent computer programs (see, for example [3], [30], and [31]) exist to aid the parts programmer in transforming blueprint/specification/drawing data into coded instructions which serve as input to the numerically controlled machine tool. It should be noted that once a tape has been prepared for a certain part, it can be stored and accessed quickly in order to produce duplicates. Additionally, small design changes can be incorporated with very limited assistance by the human operator; common methods include preparation of a new tape with the revised parameters, and

pre-emption of the tape by the human operator punching new parameters directly into the machine tool.

From the above brief description, several inherent advantages of numerically controlled machine tools are readily evident. The combination of machining activities into one machine may save set-up time losses. A derivative of this fact alone is that, although numerically controlled machines do not cut at speeds so very different from the conventional machines, the former are cutting metal a far greater percentage of the time. Further, transportation time among machine groups and queue waiting time can be reduced; therefore, the "floor-to-floor" time to process a job is readily diminished.

An attractive feature of numerical control is the nature of the content of the data. The parts programmer must reduce all instructions and measurements to a numerical form acceptable to punched or magnetized tape. Once programmed, the instructions and measurements can be transmitted by conventional data-links (note that present numerical control data format is eight-channel); herein lies a distinct benefit for an organization with naval tenders deployed around the globe -- the data link utilized for transmitting digital numerical control machining data can serve as well to transmit other pertinent data, and therefore a centralized design/engineering/parts programming/quality control organization can serve tenders in any of the seas and oceans. This concept is simply an application of computer time-sharing technology. Figure (1) represents a traditional elementary numerical control machine system [4]. Figure (2) is a functional representation of a numerically controlled machine system [4]; insertion of a data transmission link is but a slight extension. It is appropriate at this point to sound a note of caution. We have just seen how it is possible to

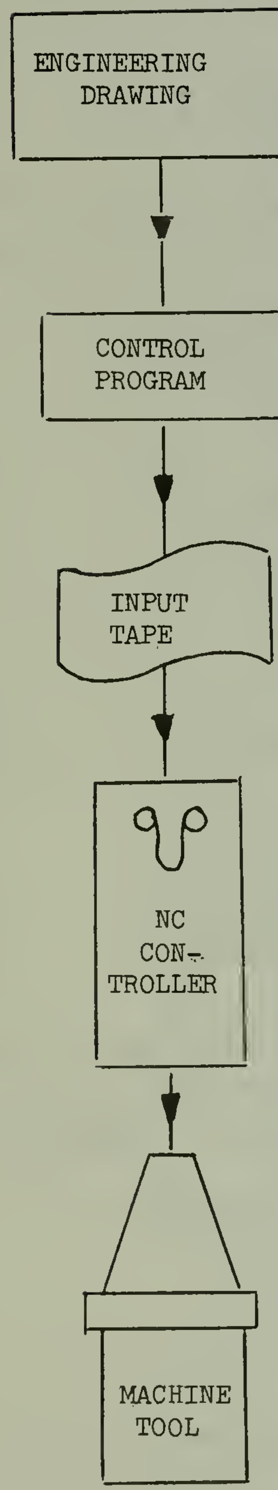


FIGURE (1) NUMERICAL CONTROL OF MACHINE TOOL

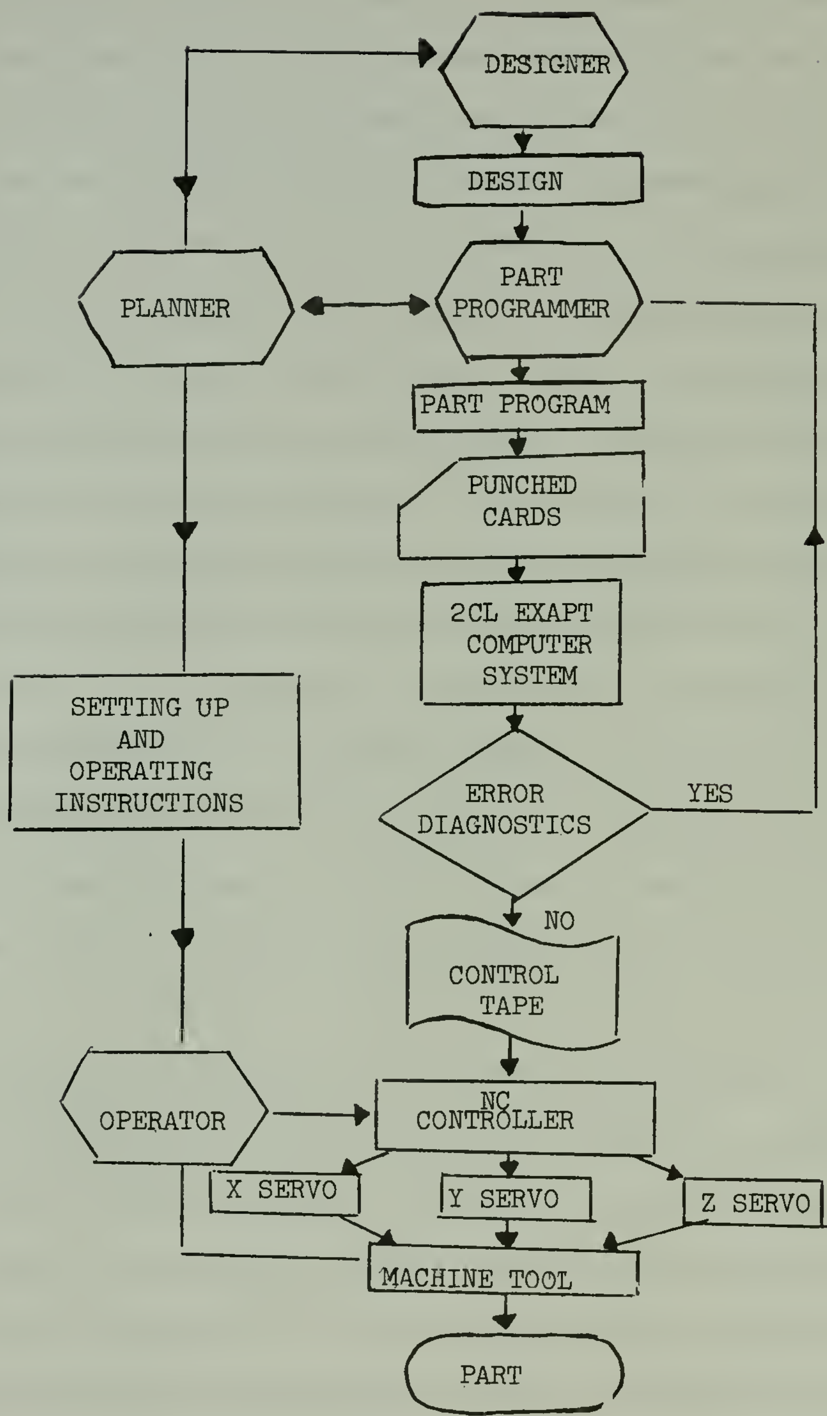


FIGURE (2) FUNCTIONAL REPRESENTATION OF THE NC SYSTEM

extrapolate a present functional system to a system which can conceivably direct machining operations around the globe. Another slight extension could be utilization of a satellite system to provide the data link, thereby allowing the centralized design/engineering/parts programming/quality control organization to control directly the operations of a numerically controlled machine tool halfway around the globe. Effectively the centralized organization would serve as a "master"; when accessed, the "master" could then generate the appropriate set-up instructions, and upon receipt of a "ready" signal would directly control the "slave" machine. Although this proposal may seem conceptually sound, one important practical point may in fact be the fatal flaw -- all information and measurements must be reduced to digital form, but if a single digit is dropped in transmission, the finished product may prove to be markedly dissimilar to the desired part. Therefore, if long distance data transmissions are considered, there must be at least some buffer system to accept the data, transmit the data back to the original sender to verify integrity, and release or store the instructions.

Jobs accomplished on numerically controlled machine tools will require less rework and therefore less scrap, given that the tape is properly prepared. The digital numerical control information is easily stored and readily accessed; economic order quantities (EOQ's have more applicability in the traditional local job shop, than in the tender environment, although multiple-item runs are occasionally accomplished on board the tender) are decreased; and finished goods inventory (on the tender this is the "gold pile") is reduced. The second-order benefits, e.g., savings from storage of less raw material or a lesser probability of a particular material stockout based on the same demand, or capability of the original raw stores to satisfy

increased demand, are evident. The superior quality control gained from using a debugged tape, and not relying on an operator to obtain close tolerances, manifests itself in less inspection time; for runs of large quantities, fewer samples will have to be checked.

Skills which are placed onto tape can be retained through transfers and changes in shop personnel. This statement is indeed true, but further inferences regarding individual skills and capabilities can not be so readily drawn. Some advocates of numerical control [22] would say that the personnel skill level could be lower in a numerical control machine shop -- supposedly, all the worker must do is to accomplish the set-up and sit back and watch. On the other hand, several users of numerical control (e.g., the Naval Air Rework Facility in Quonset Point, R.I.) have indicated no change in overall skill level, since experienced machinists are needed to ascertain whether the machine is producing the desired part or skillfully produced junk. We cannot hope here to answer the question; suffice it to say that the answer is not a simple reduction in overall skill level due to automation. We have examined several "manpower" type considerations; let us now examine some hardware associated benefits.

Numerical control can have major impacts on tooling considerations. Tool wear can be accounted for, at given speed and feed rates, by including compensatory offsets in the digital program. With this compensation, numerous stops to adjust tools are not necessary; the tool is changed only when it becomes dull. Pre-programmed cutting speeds and feeds can prolong tool life; fewer tools need to be purchased to accomplish the same workload, with less paperwork and tool storage, etc. Additionally, simple fixtures can be utilized to hold raw stock for numerical control tooling; the saving in fixture design and time spent waiting for special fixtures is marked.

James J. Childs Associates, consultants working exclusively in the field of numerical control, assisted in a study of the feasibility of using numerically controlled machine tools aboard U.S. Navy tenders, by the Logistics Management Institute. Their report [22] indicated the feasibility of placing numerically controlled lathes and machining centers on board naval tenders. An examination of tender machine shop workload indicates that these areas (in which these types of numerically controlled machines could be located) do account for the preponderant majority of the conventional workload; additionally, much of this workload is capable of being performed by numerically controlled machinery. Therefore, numerically controlled lathes and machining centers will be utilized as candidates for replacing some of their respective conventional machinery counterparts in the model to be developed. The justification, or lack of justification, for the machinery replacement is the principal question addressed by this thesis.

II. C. Model Objectives and Assumptions

In order to formulate a model of the naval tender machine shop, the objectives for this model must be clearly understood. Furthermore, certain assumptions (some for simplification and others solely for precise definition must be made).

The primary purpose of this thesis is the development of a mathematical model which will facilitate the examination of proposed changes in the naval tender machine shop machinery mix; this examination considers manpower and machinery costs, overtime usage, and shop performance. Generation of a detailed schedule, by which workers of various skill classes are assigned to work specific jobs on specific machines at given times, is <u>not</u> a goal of this model. However, the numbers of workers of various skill

classes required, the economic impacts of various decisions, and the overall machine shop performance characteristics, are important considerations to be examined.

In order to model this complex and real system, we must make certain approximations and state certain assumptions. In making these simplifications, however, care must be exercised lest the real system become too simplified, and the model not reflect the essential qualities of the real system.

We shall assume that the naval tender workload is known; this is, in fact, a rather restrictive requirement. In terms of specific jobs on specific items of equipment, such is not the case. However, large banks of historical data are maintained; from these, it is evident that many jobs are indeed recurrent activities, that ($x \pm 3$) pumps must have their shafts turned, that ($y \pm 4$) large valves must be repaired etc., on average during a typical month. These central values can be utilized to generate a representative workload for a month; perturbations about these central values can be allowed in generating workload for a multi-month planning horizon. Other very important information affecting workload is available as well: e.g., if the cycle time between regular overhauls is extended by twelve months, there clearly would be an impact on the amount of work required at the ship's force and tender levels; similarly, if future designs indicate single-shaft ships (with single firerooms and enginerooms rather than twin-shaft ships with two firerooms and two enginerooms), this impact could be forecasted. So, although we shall assume a known workload as input to our model, when such is far from ture, information appropriate to the needs of our model can be generated.

The machine capacity (in hours) and the machinery mix are decision

variables. We shall assume that the indicated required machinery is placed aboard the tender during an overhaul period, to remain on board until at least the next overhaul period. Although the machinery mix could be changed at various points in time between overhauls, clearly machinery is not going to be placed on board to meet demand in month (t), removed when not needed in months (t+1) and (t+2), and installed on board again to meet demand in month (t+3), etc.

Similarly, certain constraints can be placed on the changes of workforce from period to period. The crew embarked on board for six-month deployment is going to be relatively constant, save for emergency leaves, hospitalization, etc. The options of hiring and firing, open to the civilian job shop operator, do not really have application for the period of a deployment. We do not preclude however, modest changes in crew size between deployments.

Since hiring/firing is greatly constrained, the varying demands must be met by the utilization of overtime and undertime. Several policy constraints, e.g., the number of overtime hours as a function of the regular time workforce, could be assumed. An alternative approach, however, is allowing overtime to be an output which serves as a measure of effectiveness of the overall machine shop machinery/manpower combination. It is this latter approach which we shall utilize.

Next, we shall assume that all workers can work on all machines. In fact, most machine shop personnel coming aboard work first in the "light" section and then move to the "heavy" section; so workers in the "heavy" section can accomplish work in both sections, whereas those in the "light" section are not necessarily assignable to the "heavy" section. Since a large majority of the man-hour demand is on the "light" section, this

assumption is not a very strong distortion. The impact of this distortion could be reduced by utilization of an efficiency matrix relating worker skill classes in the "light" and "heavy" sections to the machines found in those sections. This device was not utilized because the brief field study indicated that the primary determinant of efficiency was the nature of the job, rather than the machine on which it was accomplished. It is also assumed that workers of a higher skill class can accomplish that work which is normally assigned to a lower skill class; in other words, there is downward substitutability among worker skill classes. Further, a job can be worked on by only one worker of one skill class at a time; this assumption ignores the fact that large bulky items may require more than one man to set-up on a machine, but the amount of time required for this set-up is generally quite small compared to the overall time on one machine with one worker.

No rework due to operator error or machine malfunction is considered. It should be noted that in the tender environment rework does consume many manhours and machine hours; provison for rework could be incorporated in a later model on a probabilistic basis, although generating appropriate and reliable data could prove difficult. Similarly, no provision is made for machine breakdown or preventive maintenance. The brief field study indicated that the number of times a conventional machine is completely "down" for more than one day is almost insignificant; breakdown could also be considered in a later model on a probabilistic basis, and preventive maintenance time could be explicitly considered by the addition of "jobs" requiring manpower and machine time but no throughput material.

The candidate paths through the machine shop, e.g., from a numerically controlled lathe to a conventional drill press, or from a conventional

lathe to a conventional drill press, are specified and must be followed. In other words, although alternate paths are available, certain precedence relationships exist on each path and these must be satisfied: e.g., a shaft must be turned on a lathe and then a keyway is cut on a boring mill, and the keyway cannot be cut before the shaft is turned. Although this constraint does not affect our examination in the aggregate, it is just this type of consideration which we shall see causes two major difficulties: in the actual job shop, these sequence constraints cause bottlenecks and scheduling difficulties; in the modeling of this situation, integer programming must be utilized to express the precedence relationships for each job -- for moderate size job shops with even moderate input, the number of integer variables becomes too large to be handled by present computer codes.

It is assumed that each job is broken down into its smallest components. In order to satisfy the constraint stating one man and one machine for each operation, as well as the precedence relationships, both of which were discussed above, we shall permit no overlapping of operations. A job which has two or more parts which can be worked in parallel is therefore decomposed to two or more new jobs with the appropriate due dates.

We shall allow no preemption of jobs already in process on a machine. This is not to say that a job leaving its first operation entering a queue for its second operation cannot be delayed by a higher priority job; but only that once a machine and a man have been committed to performing an operation on a specific job that operation on that job will be completed, irrespective of the higher-priority arrivals at the queue for that machine.

It is assumed that required raw materials, or satisfactory substitute materials, are always in inventory on board the tender in necessary quantities. It should be noted that, if numerically controlled machinery with

its attendant increased manufacturing capabilities is actually placed on board, further study may be necessary to determine the appropriate amounts of raw material to carry in inventory.

Another very important assumption involves the point in time for which this examination takes place: these considerations impinge on the costs assumed. If numerically controlled machinery be placed on board tenders, there will be a host of start-up transients -- large number of personnel to be trained, curricula to be developed, etc., all with high initial costs. We shall base our examination on the assumption that these transients have already occurred and that we are operating in more or less of a steady state situation; for example, given that curricula are established and that personnel on board are already trained, then the incremental training costs are simply those associated with an additional one or two weeks of schooling for the personnel being ordered to the tender machine shop.

As stated previously, we also have assumed that the naval tender remains an integral part of the fleet composition; and we have assumed that numerically controlled machinery can be made to operate in the hostile air-ocean interface environment, on board a ship, etc. Utilizing these two general assumptions, as well as the more detailed assumptions given in this section of the thesis, we can now proceed to attempt to develop a model.

II. D. Total Model - a verbal description

As discussed in Chapter I, a set of hierarchical decisions affects the operation of the naval tender machine shop. Certain decisions, e.g., fleet composition or overhaul cycle of tended ships (with attendant workload impact), are exogenous to the tender, although they do have primary long-term major facilities capacity adjustment implications. The time horizon of these decisions spans from four or five years (reflecting the time be-

tween overhauls or major restricted availabilities for a tender) to that of the ship's remaining life. It is in this long time horizon context which we must consider the major capital expenditures for the proposed numerically controlled machinery.

Another time horizon of interest must be that of a typical naval tender deployment, say six months. Crew composition (hire/fire in the civilian job shop) decisions must be made, along with consideration of acceptable overtime limits such that the shop can meet forecasted workload. An additional set of decisions is based on another time horizon, say one hour: these decisions include individual job scheduling, and assignment of individual workers to specific jobs and machines.

All of the above decisions must be made in the context of several constraints:

- machine capacity and availability limits;
- shop performance parameters (e.g., acceptable late deliveries, by number or percentage, or total lateness);
- crew composition and crew change limits;
- military doctrinal guidelines (e.g., there must be more petty officers third class than petty officers second class);
- weight margins and floor space availability for bringing aboard new equipment;
- overtime limits;
- satisfaction of precedence relationships for jobs being processed;
- definition of demand for worker skill classes and machine groups; and
- machine substitutability (numerical control for conventional).

From the above, it is obvious that we have three separate and distinct time horizons; and we have decisions to make in each time horizon -- these decisions are not distinct but are highly interdependent. For example, the

installation of numerically controlled machinery may be justified by a series of qualitative and some arm-waving over acquisition,installation, and maintenance costs versus manpower reductions and productivity gains. However justified this decision may be in a four to fifteen year time context, the tender must still deploy with a machine shop complement for six months capable of performing certain work satisfactorily on a day to day basis. Therefore it is imperative that the interactive nature of these decisions be explicitly recognized.

It may be well at this point to examine past work in the area of job shop capacity and performance. A complete literature search of these areas could form the subject area for a separate thesis; and since several excellent reviews already exist in the literature [5,26], we shall not attempt to generate a complete review.

As discussed in the first chapter,capacity expansion is usually addressed in an area referred to as strategic planning. In addition to capacity expansion, decisions at this level are directed at policies which "govern the acquisition,use,and disposition of these resources"[1]. Obviously,then,the day-to-day operational considerations are not <u>explicitly</u> considered at this broad level,even though the decisions at this level provide bounds within which the day-to-day problems must be handled.

The Holt,Modigliani,Muth,and Simon[18],and Hanssman and Hess[15] models are aggregate level models of general production facilities. These models assume fixed plant capacity and allow hiring/firing, overtime utilization, etc. These models do give insight into our intermediate time horizon, e.g., six months, but are not directly applicable to the capacity expansion problem; neither do they allow explicit consideration of detailed performance. Far greater effort has been expended in the area of detailed job shop

scheduling, but most of this effort has been undertaken assuming set outputs from (what we call) the intermediate time horizon models. Since the purpose of this thesis does not include the generation of detailed time schedules, we shall not attempt a review of these works; rather the aspect of much more interest is in works dealing with the interactions among the various levels.

Of major impact in the area of interaction is the recent work of Shwimer [29] at the Sloan School of Management, M.I.T., in which he considers both the aggregate (intermediate time horizon) and detailed scheduling problems, and the interaction between them. Shwimer proposes a decomposition into two submodels and an iterative solution procedure until some closing criterion is satisfied. It must be noted, however, that Shwimer assumes a fixed job shop capacity, whereas it is an important decision variable in our overall model. Additional work was done by Green [14], using an HMMS-type aggregated model and a detailed simulation. Both authors indicate that feedback from the detailed performance models can improve the overall shop performance.

Of especial interest at this point are conclusions regarding size, structure and solvability of a single model which examines both the intermediate and detailed time domain decisions. Shwimer [29] shows that his single model is extremely large (on the order of 38,000 constraints for a 6 week, 5 machine combination problem); furthermore, the inclusion of job precedence relationships causes a large number of integrality (1/0, either/or, binary) requirements which cannot be handled by existing computer codes. Therefore, although of general interest and a good starting point, a model for a moderate sized job shop (such as the naval tender machine shop) which examines both the intermediate and detailed level time domain decisions is

unsolvable -- and we are attempting to superpose long-range capacity expansion/capital budgeting decisions on this presently unsolvable model! Thus, we shall provide at this point but a verbal description of a proposed total model for our problem.

It is desired to minimize the sum over all time periods under consideration of the following costs:

- manpower costs at regular time work;
- overtime cost (although a sailor on board does not receive any additional money whether he works eight or eighteen hours, there certainly are penalties incurred by working personnel varying degrees of overtime);
- turnover of personnel (hire/fire in the civilian sector - due to fluctuating workload) costs;
- acquisition, installation and incremental operation, maintenance, and overhead costs attendant to bringing numerically controlled machinery on board;
- rework and wastage of raw material costs;
- tardiness penalties;
- quality/reliability assurance costs; and
- numerically controlled machinery programmer manpower costs.

This minimization of total costs over all of the time periods under consideration must be accomplished under a set of constraints. A partial listing of these constraints was provided earlier in this section. The following listing completes the set of constraints:

- balance of workforce manpower available from one period to the next period (this constraint is analogous to the continuity equation from fluid mechanics);
- limited workforce manpower of each skill class available in each time period;
- lower and/or upper bound machine utilization limits;
- number of jobs being worked on a machine group during the shortest time considered limited by the number of machines within that machine

- group;

- the number of jobs being worked by a member of a labor skill class during the shortest time considered limited by the number of men within that skill class;

- the aggregation of all productive work during the shortest time period considered, into larger time units, must be consistent;

- non-negativity of decision variables (e.g., cannot work a negative number of hours on a job); and

- integrality of some of the decision variables (e.g., the number of machines and workers must each be integral).

In a previous portion of this section, it was noted that a subset of this total model (i.e., a model considering only the intermediate and detailed time decisions, which assumed a fixed shop capacity) has been shown to be too large to solve with presently available computer codes for mixed-integer linear programming problems. Furthermore, with reference to the various points made regarding the impacts of various time horizons, a single mathematical model is inappropriate: an integrated/detailed large production model does not take sufficient cognizance of the distinct characteristics, time horizons, and scopes of the various decisions. A verbal description of a proposed total model has been presented, however, to indicate the scope and complexity of the total problem. In the next chapter, we shall present a method for decomposing the proposed total model into two submodels; an appreciation of the total problem and the total model herein described will be useful in understanding the proposed decomposition and solution.

CHAPTER III

DECOMPOSITION OF THE TOTAL MODEL

III. A. Proposed Solution Scheme

In the past chapter we presented a verbal description of a proposed total model; certain aspects of size and structure were discussed, and it was noted that such a proposed total model would be unsolvable given present computer technology. Additionally, we made several observations about the various time horizons involved in the model, especially their impacts on various decisions and their interactive nature. We shall utilize these different and special time horizon characteristics as guides in decomposing the total model into two smaller submodels.

Although it is theoretically possible to develop iterative procedures to link aggregate and detailed models by sequential adjustment of lower level actions in a manner to guarantee convergence to an optimum final plan (see, for example, Dantzig and Wolfe [9]), this approach seems neither computationally nor managerially feasible in the present case. Hax [16] has suggested a way in which to partition the strategic and tactical planning activities of a firm, providing an interactive hierarchical system which attempts to avoid some of these pitfalls. Much of the reason for the structure and unsolvability of a model approach was the fact that long-range decisions, say the expenditure of capital for purchasing numerically controlled machinery, were intimately tied to short-range decisions, say scheduling of jobs and assignment of workers for a one-hour period, all within one large and complex "maze". Decomposition of the total model yields two smaller submodels, partitioned along the time dimension; these models are as follows:

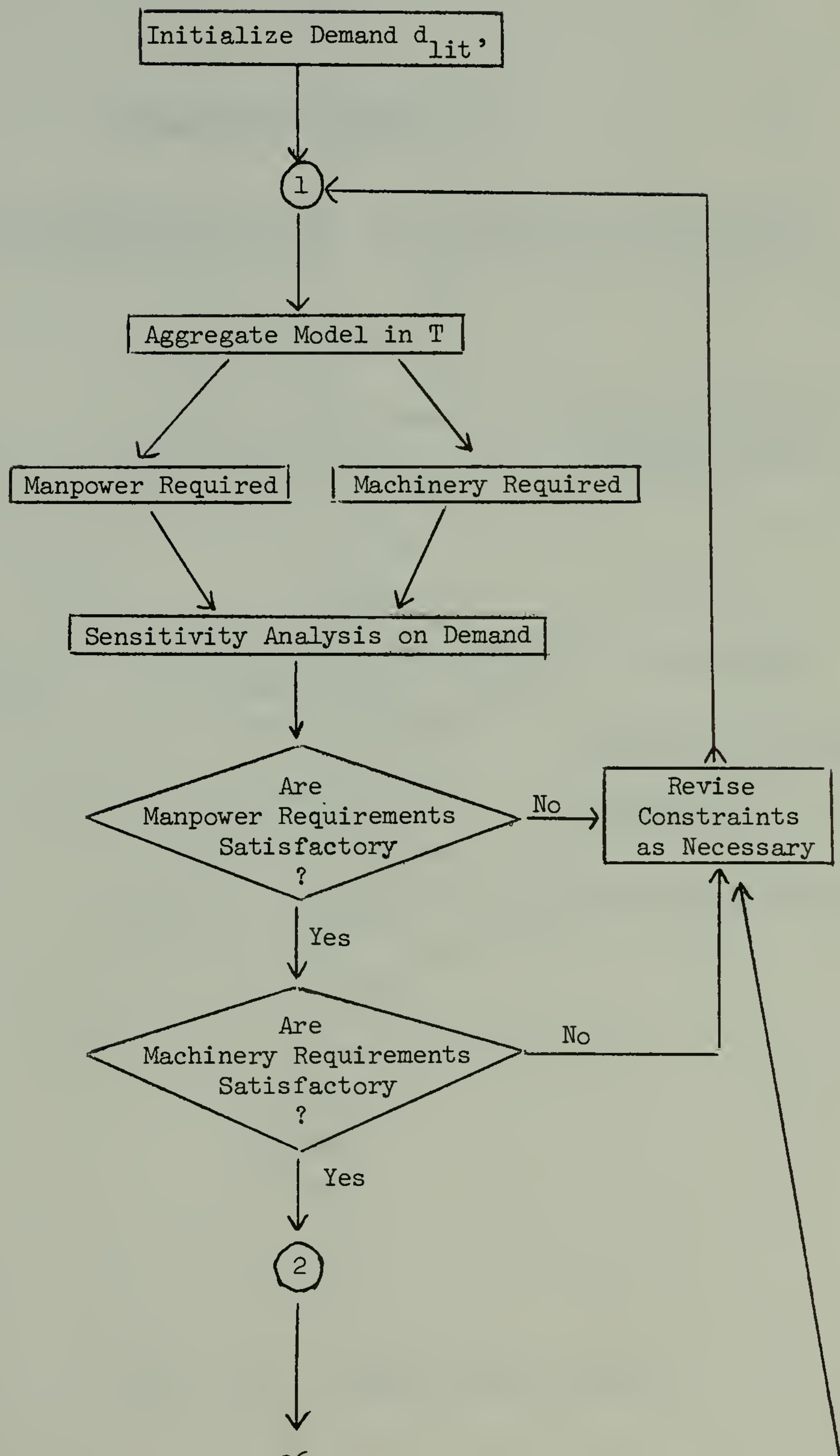
-- the aggregate model, utilizing forecasted demand as input, wherein decisions regarding machinery purchases and work-force size are

made; and

-- the detailed model, utilizing the machinery configuration and work-force schedule derived in the aggregate model as inputs, wherein scheduling and assignment decisions are simulated, and shop performance and utilization of manpower and machinery are determined.

As can be seen by the above decomposition, the time horizon of the aggregate model is at least on the order of the length of a deployment, say six months, whereas the detailed model addresses decisions on a daily or hourly basis. Indeed the two models are coupled and highly interactive: the aggregate model is oblivious to daily or weekly changes in the demand patterns, and does not recognize bottlenecks or queue formations before machine groups -- but the output of the aggregate model bounds the daily and hourly operation of the tender machine shop; similarly, the utilization of manpower (under-time or overtime), completely ignored in the aggregate model, coupled with measures of shop performance (e.g., number of tardy jobs, or mean tardiness of jobs), can alter the machinery configuration and/or work-force allocations by labor class determined by the aggregate model.

It is proposed that the two models be solved sequentially, the aggregate model first, with iterations between the two models as necessary. Figure (3) illustrates the proposed solution scheme. As stated above, the outputs of the aggregate model are tables of machinery requirements and manpower requirements. If these requirements are both satisfactory, then they can be utilized as input to the detailed simulation. If the manpower or machinery mix requirements are not satisfactory (e.g., a manning structure with more second class petty officers than third class petty officers, which may violate military manning doctrines), then constraints can be modified and/or added as necessary.


Initialize Demand d_{lit},
1
Aggregate Model in T
Manpower Required
Machinery Required
Sensitivity Analysis on Demand
Are Manpower Requirements Satisfactory ?
No
Revise Constraints as Necessary
Yes
Are Machinery Requirements Satisfactory ?
No
Yes
2

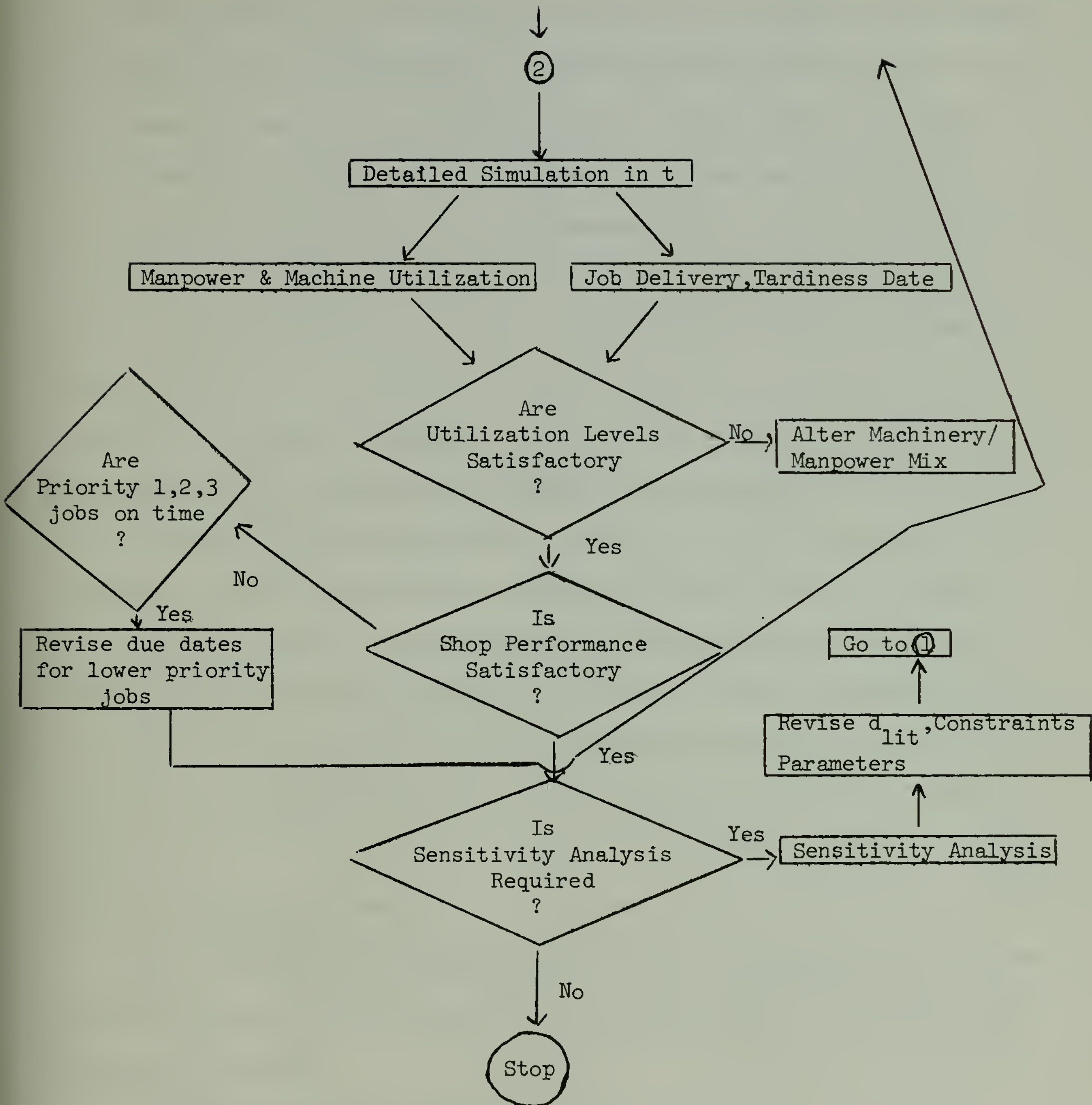


Figure (3): Proposed Solution Scheme

Once a satisfactory combination of manpower and machinery requirements is obtained in the aggregate model, the detailed simulation can be run. If the manpower or machinery utilization levels are unsatisfactory, a change in the overall cost structure (e.g., hiring or firing) may be indicated, which changes the requirements in the aggregate model. If the utilization levels are satisfactory, then the shop performance (in terms of delivery dates versus due dates) can be checked. In the actual tender environment, those jobs with lower priorities would be "slipped" for completion at a later time. Once both acceptable utilization and shop performance levels are obtained, then a sensitivity analysis can be accomplished. The results of the sensitivity analysis may indicate that some of the parameters, constraints, or demand characteristics should be modified, and the problem is run again starting with the aggregate model. Having examined the general framework in which the two models fit, let us move next to defining each of the models. In the last section of this chapter, after appropriate symbolic notation is introduced, methods of model interaction will be more fully discussed.

III. B. The Aggregate Model

Prior to presenting the mathematical form of the aggregate model, some symbolic notation will be described. The indices utilized in the aggregate model are as follows:

-- i indexes machine groups, $i = 1, 2, \dots, I$

-- l indexes workforce skill classes, $l = 1, 2, \dots, L$

-- t indexes aggregate level time periods, $t = 1, 2, \dots, T$

Let us examine more clearly the machine groups. In the second chapter it was determined that the candidate groups for substitution of numerically

controlled machines, at the present time, were the standard lathes in the light section and the universal/plain milling machines in the heavy section. Each of these two classes of similar machines, then, should be examined as separate machine groups. The remaining machines can be grouped by some sensible method -- it will be seen later that the remaining machines of the light section can be grouped into one large group, since the tender machine shop is to be labor-limited in this area, and similarly so with the remainder of the heavy section.

The workforce is divided into skill classes corresponding to the skill/pay rates of petty officers first, second and third class; further, although two additional distinct skill/pay rates are assigned to the shop, these will be grouped into a fourth class (this simplification justified by a small differential in annual pay for these two lower enlisted groups; also, the machine shop supervisors would desire the higher of the two two skill/pay rates aboard). It is assumed, in this thesis, that the number of chief petty officers required for shop administration and supervision is constant for all machinery configurations; since these costs are not variable, they do not enter into our analysis.

The aggregate level time periods which we shall consider are months. This length of time is chosen for several reasons: 1) convenience; 2) much demand data is gathered on a monthly basis; and 3) the deployment and immediate manpower planning horizon is typically on the order of six months. Those parts of the total model dealing with decisions based on one or more months demands or capital expenditures will be included in our aggregate model; those parts of the total model dealing with hourly or daily decisions will intentionally be placed in the detailed model to be described in the

next section of this thesis.

The mathematical formulation of the aggregate model is as follows:

$$\text{MINIMIZE} \left\{ \sum_{t=1}^{T} \sum_{l=1}^{L} C_{lt} M_l + \sum_{t=1}^{T} \sum_{i=1}^{I} C_{it}{*}N_i{*} + \sum_{i=1}^{I} (1) R_i \right\}$$

subject to

(1)	$X_{lit} + f_i X^*_{lit}$	$= d_{lit}$	all l,i,t
(2)	$\sum_{l=1}^{L} X_{lit} - \underline{h}_{it}\underline{N}_{it}$	$= 0$	all i,t
(3)	$\sum_{l=1}^{L} X^*_{lit} - \underline{h}_{it}{*}\underline{N}_{it}{*}$	$= 0$	all i,t
(4)	$\underline{N}_{it} - N_i$	≤ 0	all i,t
(5)	$\underline{N}_{it}{*} - N_i{*}$	≤ 0	all i,t
(6)	$\sum_{l=1}^{L} X_{lit}$	$\geq k_i \sum_{l=1}^{L} d_{lit}$	all i,t
(7)	$R_i + N_i$	$\leq b_i$	all i
(8)	$a_i R_i - k' a_i{*}N_i{*}$	≥ 0	all i
(9)	$\sum_{i=1}^{I} w_i{*}N_i{*} - \sum_{i=1}^{I} w_i R_i$	$\leq m$	
(10)	$\sum_{i=1}^{I}{}' X_{lit} - h_{lt} N_{lt}$	$= 0$	all l,t
(11)	$\sum_{i=1}^{I} X^*_{lit} - h^*_{lt} N^*_{lt}$	$= 0$	all l,t
(12)	$N_{lt} + N_{lt}{*} - M_{lt}$	$= 0$	all l,t
(13)	$k'' M_{lt} - M_l$	≤ 0	all l,t

(14) X_{1it}, X^*_{1it}, $\underline{N}_{it}$, $\underline{N}_{it}^*$, N_i, N_i^*, R_i, N_{1t}, N_{1t}^*, M_{1t}, M_1 all ≥ 0

(15) N_i, N_i^*, R_i, M_1 all integer

The following is a list describing each of the decision variables included in the aggregate model:

X_{1it} is the number of hours of conventional machine time used by workers of skill class 1 on machine group i in time period t;

X^*_{1it} is the number of hours of numerically controlled machine time used by workers of skill class 1 on machine group i in time period t;

$\underline{N}_{it}$ is the number of conventional machines in machine group i required to satisfy the workload demand for that machine group in time period t;

$\underline{N}_{it}^*$, is the number of numerically controlled machines in machine group i required to satisfy the workload demand for that machine group in time period t;

N_i is the number of conventional machines in machine group i which will satisfy the workload demand for that machine group, in any time period t = 1, 2 ..., T;

R_i is the number of conventional machines removed from machine group i;

N_{1t} is the number of skill class 1 workers required to meet the workload demand on conventional machinery in time period t;

N_{1t}^* is the number of skill class 1 workers required to meet the workload demand on numerically controlled machinery in time period t;

M_{1t} is the sum of the numbers of skill class 1 workers required to meet the workload demand on both conventional and numerically controlled machinery in time period t; and

M_1 is the sum of the numbers of skill class 1 workers required to meet the workload demand on both conventional and numerically controlled machinery, in any time period t = 1, 2 ..., T.

The following is a list describing each of the costs included in the aggregate model:

C_{1t} is the composite standard military pay rate (salary and benefits equivalent) charged for a worker of skill class 1 in time period t; and

C_{it}* is that share of the acquisition, installation, and incremental operation, maintenance, and overhead costs attendant to bringing aboard a numerically controlled machine into machine group i, attributable to time period t.

Several comments regarding these costs and others are necessary at this point:

-- overtime or undertime cost is not included, but rather is utilized as a measure of performance for the overall machinery/manpower mix;

-- turnover of personnel (hire/fire in the civilian sector-due to fluctuating workload) costs are not included: discussions of constraints (10) through (13) later in this section will clarify this point;

-- rework and wastage of raw materials costs are ignored in this study, mainly due to the difficulty of obtaining reliable data; this simplification is not of great magnitude; further, once a numerical control program is debugged, multiple items can be run with very little probability of rework and wastage, so incorporation of numerical control technology will tend to decrease these costs;

-- tardiness penalties are not explicitly included, but like overtime tardiness is utilized as a measure of performance for the overall machinery/manpower mix; determination of appropriate tardiness cost coefficients is difficult (how much penalty is incurred if a destroyer cannot get underway to meet a commitment?; how much penalty is incurred if a destroyer gets underway with a less safe or less reliable power plant or weapons system?);

-- quality/reliability assurance will probably gain greater attention in the future, requiring the assignment of inspection manpower; incorporation of numerical control technology decreases the inspection necessary on large lots, so at least these quality/reliability assurance costs will not increase; at this point, they are ignored as not depending on the machinery configuration;

-- numerically controlled machinery programmer manpower costs will obviously increase with the application of numerically controlled machines to the tender machine shop; once a sizable library of programs is established and all shop personnel are trained in the use of these machines, however (our "point in time in the future" assumption), then programs can be obtained from a central source for all tenders and programmer manpower on board becomes insignificant for our model; and

-- note a third cost component in the objective function with a unity coefficient: recall that R_i is the number of conventional machines removed from machine group i, and then this cost component discourages

the removal of more machines than necessary to satisfy all of the constraints; this point will be examined more fully later in this section when constraint (7) is discussed.

The following is a list describing each of the parameters and/or constants included in the aggregate model:

f_i is a productivity factor reflecting an increased throughput rate for jobs which are accomplished on a numerically controlled machine rather than on a conventional machine, for a particular machine group i -- for example, if in the aggregate a set of jobs requires 100 hours of numerical control lathe time or 300 hours of conventional lathe time, then the productivity factor for a numerical control machine in the lathe machine group would be 3;

d_{1it} is the number of hours of conventional machine time to be performed by workers of skill class 1 on machine group i in time period t, the demand;

$\underline{h}_{it}$ is the number of hours that a machine in machine group i must be available for the accomplishment of productive work during time period t;

$\underline{h}_{it}$* is the number of hours that a numerically controlled machine in machine group i must be available for the accomplishment of productive work during time period t;

k_i is a constant ($0 \leq k_i \leq 1$) which reflects the fact that a certain amount of the demand workload can not be (readily or at all) accomplished on a numerically controlled machine: in context of constraint (6), if k_i=0 then all of the demand can be accomplished on numerical control machinery, whereas if k_i=1.0 then all of the demand must be met by work on conventional machinery;

b_i is the original number of conventional machines in machine group i, prior to any substitution by numerically controlled machinery;

a_i is the deck area required for a machine in machine group i;

a_i* is the deck area required for a candidate numerical control machine in machine group i;

k' is a constant which can be utilized to introduce more (or less) free deck space in the tender machine shop: k' can be seen to be the ratio of the areas of removed machines to the areas of numerical control machines brought aboard, and as such reflects the fact limited deck area exists for the mounting of machinery;

w_i is the weight of a conventional machine to be removed from machine group i;

w_i^* is the weight of a candidate numerical control machine (including necessary foundations, etc.) in machine group i;

m is the (weight) margin which reflects naval architecture (weight constrained design) or other design constraints on the bringing aboard of additional weight;

h_{lt} is the number of manhours that a worker of skill class l must be available for productive work on conventional machinery during time period t;

h_{lt}^* is the number of manhours that a worker of skill class l must be available for productive work on numerically controlled machinery during time period t; and

k" is a constant used in smoothing manpower requirements on second and later iterations through the aggregate model; k" = 1 for the first iteration; use of k" will become clearer when constraint (13) is discussed later in this section.

Having defined the symbolic notation and described the decision variables, parameters, and costs in our aggregate model, we can now proceed to a description of each of the constraints (note that the constraint numbers in parentheses refer to those provided in the mathematical formulation earlier in this section on page 40):

(1) The demand for worker skill class l on machine group i in period t must be satisfied by some combination of conventional and numerical control machine productive manhours [for all machine groups, skill classes, and time periods];

(2) The number of conventional machines in machine group i during time period t must be equal to the number of conventional machine hours worked by all skill classes in that group, divided by the required availability for that time period [for all machine groups and time periods];

(3) The number of numerical control machines in machine group i during time period t must be equal to the number of numerical control machine hours worked by all skill classes in that group, divided by the required availability for that time period [for all machine groups and time periods];

(4) The number of conventional machines in machine group i on board must be greater than or equal to that number required during <u>any</u> time period t [for all machine groups and time periods];

(5) The number of numerical control machines in machine group i on board must be greater than or equal to that number required during <u>any</u> time period t [for all machine groups and time periods];

(6) At least a certain fraction of the demand for machine group i during time period t must be met by conventional machine time -- since numerical control is not directly applicable to all of the demand [for all machine groups and time periods];

(7) The number of conventional machines in machine group i removed must be less than or equal to the difference of the original number on board and the number actually required as determined above [for all machine groups];

(8) Limited deck area exists for replacement of machinery [for all machine groups];

(9) The differences between the weights of replacement and removed machinery, when summed over all groups, must satisfy some weight margin;

(10) The number of workers of skill class l during time period t on conventional machines must be equal to the number of conventional machine hours for all machine groups worked by that skill class, divided by the appropriate maximum allowable hours worked in time period t [for all skill classes and time periods];

(11) The number of workers of skill class l during time period t in numerically controlled machines must be equal to the number of numerical control machine hours for all machine groups worked by that skill class, divided by the appropriate maximum allowable hours worked in time period t [for all skill classes and time periods];

(12) The sum of the manpower of skill class l required for both conventional and numerical control machine work in time period t must equal the total manpower requirement for that skill class in that time period [for all skill classes and time periods];

(13) The manpower of skill class l must be greater than or equal to (a constant k"times) that number of skill class l workers required during <u>any</u> time period t [for all skill classes and time periods];

(14) Non-negativity required of all decision variables; and

(15) Some of the decision variables are allowed to take on only integer values.

Let us briefly amplify the description given for several of the constraints.

Constraint (7) allows the determination of a number of machines to be removed from a machine group, R_i by taking cognizance of the actual required number and the initial number of machines in the group, N_i and b_i respectively. Note, however that the objective function penalizes the solution by one dollar for every machine removed, therefore tending to minimize the number removed. This constraint and penalty in the objective function are included in this model for three purposes: 1) Nelson [27] favors the labor-limited systems; 2) the workload demand on which this study is based is for a (relatively) peace-time environment, whereas in a combat situation a huge step increase would be expected -- additional personnel ordered aboard would be much more effective and productive if the tender machine shop were not already machine-limited; and 3) to remove presently excess machinery costs money -- note that this last reason implies that no superior use for the space which could be vacated by the extra machinery does exist.

Constraints (2) and (3) determine the numbers of conventional and numerical control machines required each month. Constraints (4) and (5) then impose the fact that the numbers of each type of machine carried on board at all times must exceed or be equal to the required number at <u>any</u> time. In effect, then, if a machine is needed in time (t+4) only and not in any of the other five time periods in the horizon, it must be placed aboard prior to a deployment and kept on board throughout the deployment.

Constraints (10) and (11) determine the required manpower for conventional and numerical control machinery during each month. Constraint (12) simply causes the sum of the two manpower needs to be determined. And constraint (13), when $k''=1.0$, requires that a man of skill class 1 needed

at any time during the planning horizon be ordered aboard at the start of the time horizon and kept aboard until the end of the planning horizon (in our case, a 6-month deployment). The factor k" is provided for use on subsequent runs in an iterative process: e.g., if the overtime utilization of skill class 1 exceeds the desires of the decision-maker, k" can be set greater than 1.0, thereby requiring additional personnel aboard.

In summary, the decisions in the aggregate model regarding:

- -- the numbers of conventional machines in each machine group during each aggregate time period,
- -- the numbers of numerically controlled machines in each machine group during each aggregate time period, and
- -- the numbers of workers in each skill class required aboard during each aggregate time period

are subject to constraints concerning:

- -- limited manpower availability,
- -- limited machine capacity,
- -- limited shop floor (deck) area for capacity expansion,
- -- limited weight margin,
- -- supplying sufficient manpower and machinery to meet required demand,
- -- limited machine substitutability, and
- -- removal of extra machines.

III. C. The Detailed Model

The outputs of the aggregate model are a set of manpower requirements, listed by skill class, and a proposed conventional/numerical control machinery mix; these outputs have been generated such that the aggregate objective function has been minimized. We have actually begun, therefore, to answer the question of whether numerical control technology should be

applied to the naval tender machine shop environment. It will be the purpose of the detailed model to yield additional information regarding the advisability of substituting numerically controlled machines for the existing conventional machinery. Let us reiterate that the specific decision regarding scheduling of jobs and assignments of specific workers to machine groups and jobs are not primary goals of the detailed model; rather, the detailed model should be so designed as to test the performance of the recommended manpower/machinery mix generated by the aggregate model.

Utilization of simulation has been recommended for similar "detailed"-type problems by Shwimer [29], Green [14], May [25], and Baker and Dzielinski [2]. Prior to following their lead, it may be appropriate to examine what other alternative methods are available for determining the impact of the decisions generated by the aggregate model. In the absence of a solvable mathematical model, there are only two other options: 1) simulation; and 2) experimentation with the real-life system. Since the latter alternative, i.e. experimentation on board an actual naval tender, would quite obviously be very expensive, simulation has been chosen. Within simulation, possible manpower/machinery configurations can be examined, as can be the workload forecasts used as inputs, and the approximate results used by the decision-maker.

As discussed in the assumptions listed in an earlier chapter, the nature of the work being processed by the naval tender machine shop is such that each operation requires at a given time one machine within a machine group and one worker of a certain skill class. For those jobs which can be split up into components and worked in parallel, we shall divide them into separate jobs with the appropriate due dates, in order to maintain the one

job-one machine-one worker rule; similarly, although a very small number of jobs require more than one sailor to set up on a machine (in the brief survey conducted, three jobs in 167 considered for a month's typical work-load fell into this category), we shall maintain the one job-one machine-one worker rule throughout this study.

We now have the building blocks for generating a simulation model. These building blocks are the following:

-- jobs which flow through a network of operations; where the sequence, machine groups, worker skill level, and service times at each step are a function of and specified by the job itself;

-- activities which utilize multiple resources (in this study the resources are machines, manpower, and material), and require time to perform an operation;

-- flow lines connecting a network of activities, defining a sequence of operations, and denoting a direction of flow; and

-- boundary elements, i.e. points of job origination (sources) and job termination (sinks).

In addition to the above building blocks of a network for simulation, there are certain analytical aspects which the simulator must address. These real-system functions and operations are the following:

-- service times to accomplish operations on jobs at activities are stochastic, and as stated above, are direct functions of the individual characteristics of the jobs;

-- job routing through alternate paths within the network;

-- queue disciplines, whereby job routing among possible and acceptable paths within the network is accomplished with respect to the location,numbers, and priorities of other jobs in the system; and

-- operating schedules for the system, whereby standard workdays can be established, and the system closed or open to arriving jobs according to some pre-determined role.

TRANSIM [28] is a general purpose system similator which can process problems of the type of the present detailed model; Monte Carlo methods

are used in the simulation process. TRANSIM was developed at the University of California, Los Angeles, School of Engineering and Applied Science. Additionally, TRANSIM possesses several characteristics of interest in the proposed iterative process; these include the following:

-- a calendar of events contains a chronological listing of scheduled events, designating when and where each event (in our case, release or termination of a job) will occur;

-- an event-oriented clock incremented in steps to subsequent chronological events; and

-- maintenance of a record of current states of the system such that a chronological record of events can be printed out, utilization and performance evaluated.

Figure (4) is a descriptive flow chart of the process followed by the simulator. A job arriving in the shop is characterized by its priority, the minimum skill class worker which it requires, its preferred and acceptable alternate (where applicable) paths through the shop, and the times required at each node on the respective paths. For example, consider a job specified by P/L/R-ab/S-cd: the first digit refers to priority (1 through 9), which is determined exogenous to the simulator by combining the requesting ship's assigned priority (1,2,3,4) and the initial slack (due date minus arrival date minus expected operating time); the second digit refers to the minimum skill class worker (1 through 4) required to accomplish the job; the next group refers to the preferred path (in this case R) and the time tables representing the time distributions required on each node on the path where the first time table refers to the first node and the second time table to the second node; the last group refers to an acceptable alternate path (in this case S) and the time tables describing the operating time distributions at each node on the path. Appendix F lists the possible paths included in the network. Appendix D

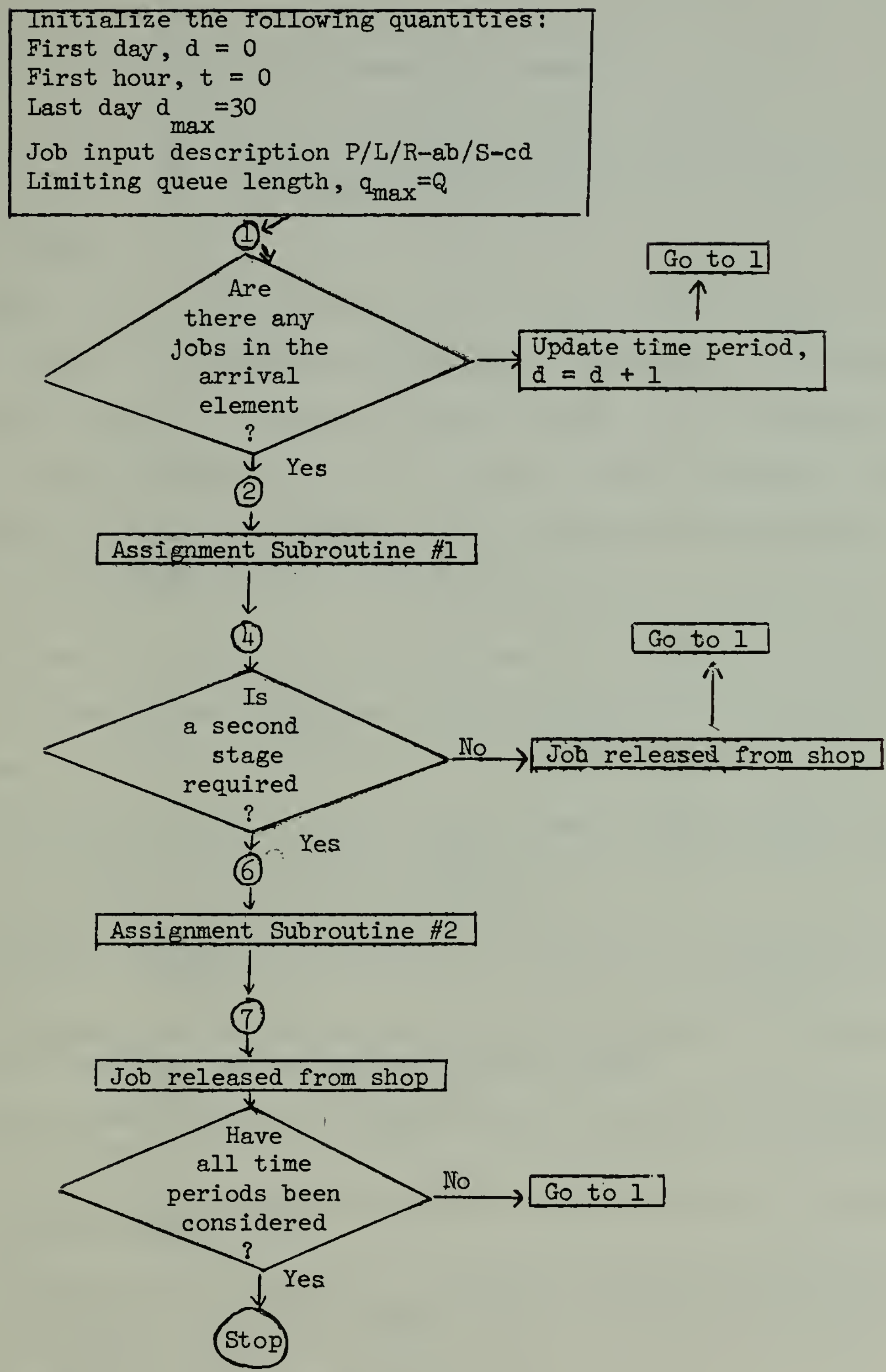


Figure (4): Detailed Model Simulation Flow Chart

lists the 178 jobs which were utilized as input to the simulation; additionally, these jobs served as the demand requirements d_{1it} for month 1 of the aggregate model described in the previous section. Appendix E lists the characteristics of the job accomplishment time histograms utilized in the simulation model.

Figure (5) is a descriptive flow chart of Assignment Subroutine #1 shown in figure (4). Assignment Subroutine #2 is identical to Assignment Subroutine #1, with the exception that the entering and exiting nodes are numbered 6 and 7 respectively, and the internal nodes are numbered differently; due to the similarity between the two assignment subroutines, a separate descriptive flow chart is not shown for the second subroutine.

Many important elements have been purposely left out of the detailed simulator. Among those elements not being considered we can mention the following:

-- Labor-class downward substitution, whereby an idle worker of higher skill (and lower skill class index 1) can be assigned work when lower skill workers are all assigned;

-- Machine breakdown, which could be included on a probabilistic basis in later refinements;

-- Scheduled machine maintenance during which periods the machine is not capable of accomplishing productive work;

-- Job arrivals during the workday which are input as of the beginning of the day;

-- Job arrivals on weekends, which are input at the start of the next regular workday; and

-- Training and working-party requirements which remove various skill class workers from the assignable labor pool during the workday.

III. D. Aggregate/Detailed Model Interaction

In this chapter a method has been presented whereby the total problem can be decomposed into two submodels. The primary dimension in the decom-

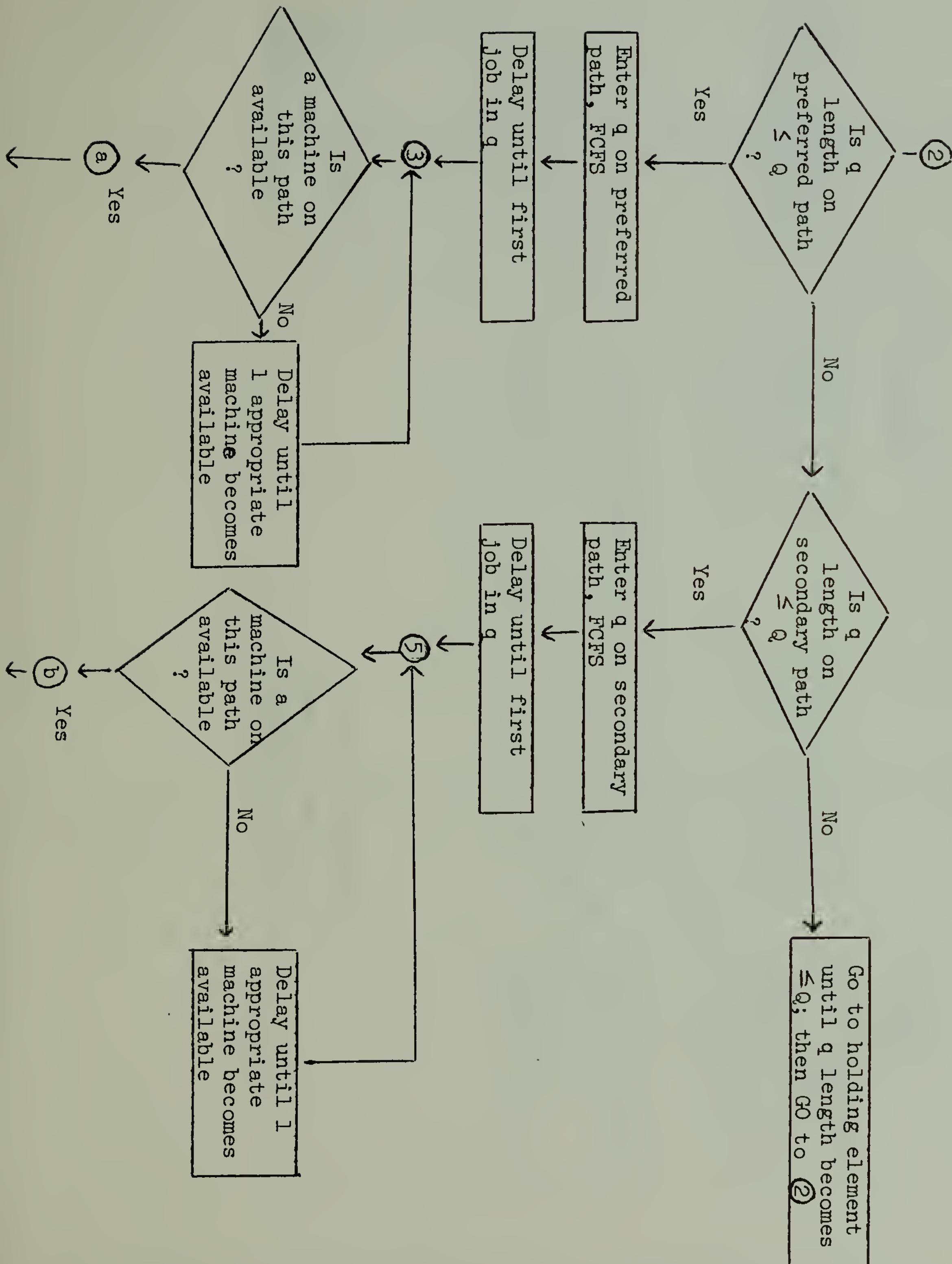


Figure (5) Descriptive Flow Chart of Assignment Subroutine #1

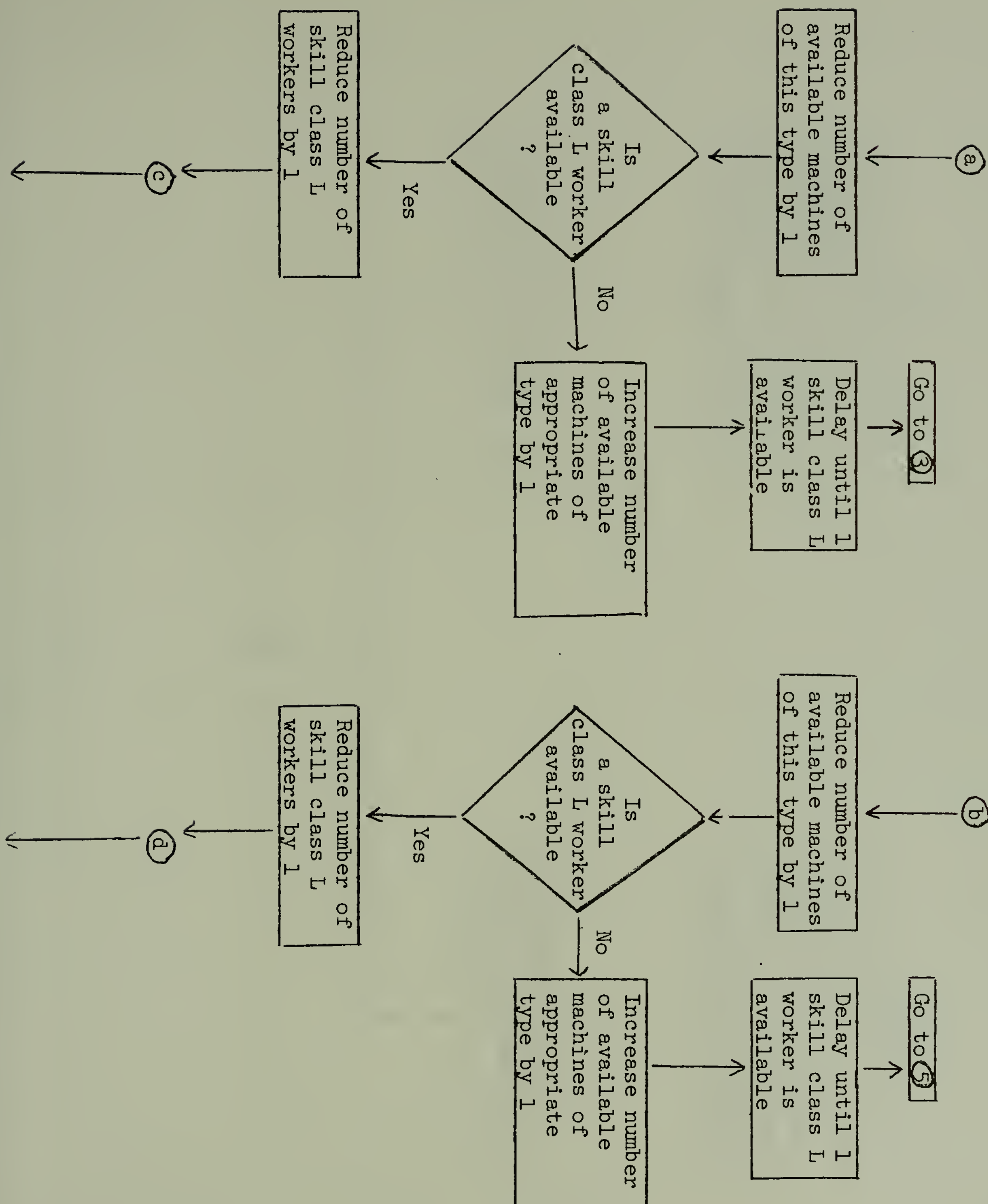


Figure (5) Descriptive Flow Chart of Assignment Subroutine #1

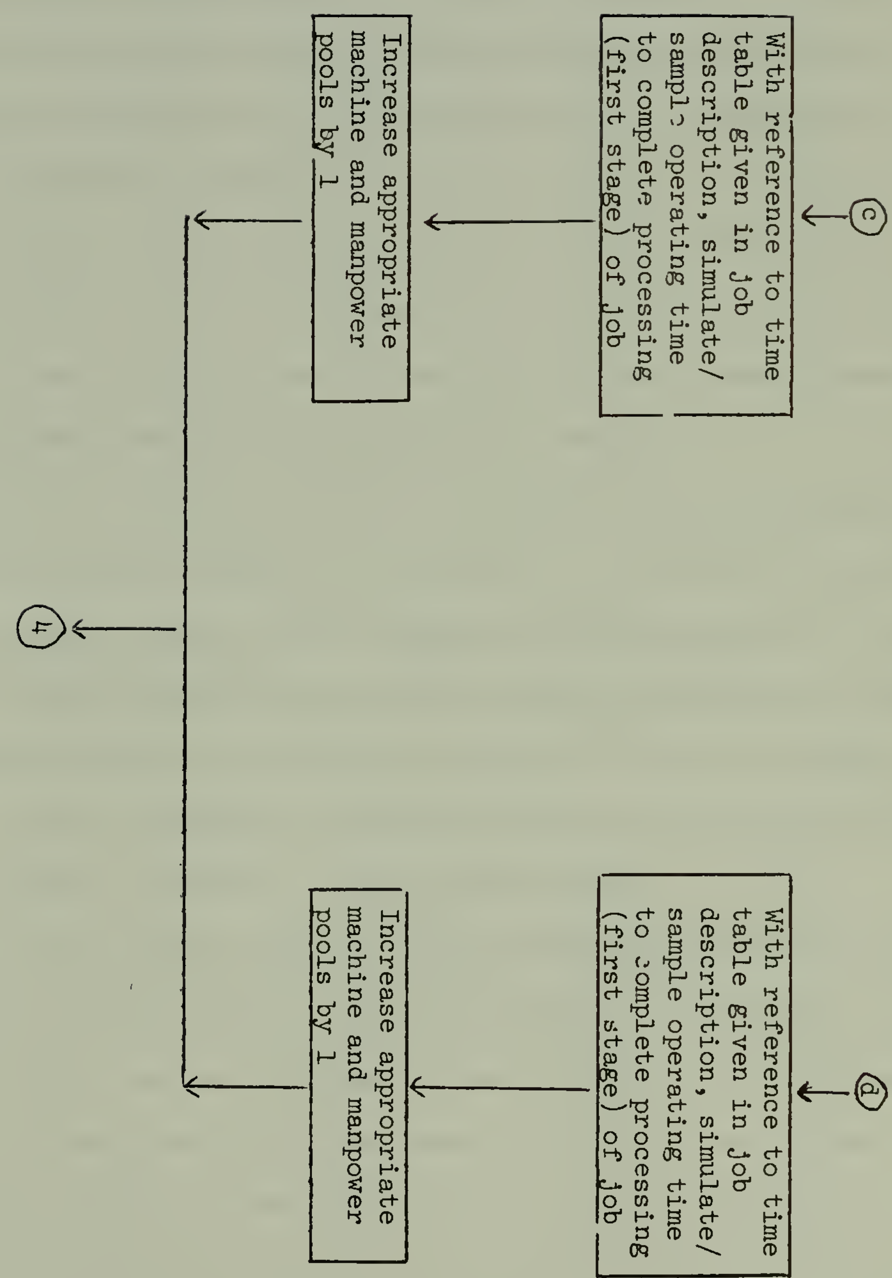


Figure (5) Descriptive Flow Chart of Assignment Subroutine #1

position and the solution scheme is time -- the longer-term decisions were placed in the aggregate model and the short-term hourly operational decisions were placed in a detailed model which is in fact a simulation. It may be well here to stress the implicit values of using time as the determinant dimension for partitioning the total model into two parts: the long-term decisions require aggregated information such that all of the important dimensions are included, and the unnecessary lower level considerations are not presented in such detail as to becloud the issue; the short-term decisions require as input those decisions made at the higher levels, thereby permitting the disaggregated lower level decisions to be made.

Specifically, the decisions made by the aggregate model were manpower and machinery requirements, including the purchase of numerically controlled machinery. The aggregate model did not address such complications as bottlenecks or queue formations which do arise in the hourly operation of a naval tender machine shop; however, the detailed simulator did address problems of these types, and the information gleaned from the simulation may indicate necessary modifications to be made in the aggregate model.

The original form of the aggregate model determined manpower and machinery requirements based solely on demand; from the aggregate model, manpower and machinery utilization rates were determined; and similarly from the detailed model, manpower and machinery utilization rates were determined. After examination of these outputs, other characteristics of interest to the decision maker may be involved. A set of rank constraints may be required to maintain a pyramid-like manning structure; this set of constraints may be expressed in the aggregate model as follows:

$$M_1 < M_2;$$

$$M_2 < M_3; \text{ and}$$

$$M_3 < M_4.$$

Another characteristic may refer to the utilization rates of manpower as determined by the aggregate model. In order to prevent excessive undertime the following constraint may be used:

$$\sum_{t=1}^{T} M_{1t} - T\,(0.75)\,M_1 > 0,$$

on the appropriate labor classes 1 over T aggregate time periods; this constraint would require the average utilization of the workers of skill class 1 to be at least 75 percent over the T time periods. Alternately, the detailed simulation, in handling the probabilistic nature of job arrivals and job accomplishment times, may indicate utilization rates which are excessive; in this case the following constraint could be used as the appropriate skill class 1:

$$\sum_{t=1}^{T} M_{1t} - T\,(0.90)\,M_1 < 0,$$

over T aggregate time periods; this particular constraint would require the average utilization of the workers of the appropriate skill class 1 to be less than 90 percent over T time periods.

Similar types of constraints may be utilized for the machinery mix and utilization. For example, if the decision-maker desires to impose an upper bound on the ratio of numerically controlled lathes to conventional lathes to conventional lathes, the following constraint could be utilized:

$$N_1^* - 3N_1 < 0,$$

which would require the machinery mix to provide at least three conventional

lathes for each numerically controlled lathe. Whereas the aggregate model may indicate, say, three numerically controlled lathes, the detailed simulation may indicate only minimal utilization of all three numerically controlled lathes; then, the decision-maker could set or bound at 2 the number of numerically controlled lathes using one of the following constraints:

$$N_1^* \leq 2, \text{ or}$$

$$N_1^* = 2.$$

Alternately, the machine utilization could be treated in the aggregate model in a manner identical to that of the manpower utilization treated above.

Incorporating these changes in the aggregate model may cause other changes in the manpower or machinery mix; this revised set of requirements could then be input to the detailed simulation; the results of the latest simulation could then be examined; and the iterative process could be repeated until some closing criterion (e.g., utilization of manpower or machinery below or above some limit; shop performance in terms of tardiness reduced by some specified amount) were satisfied. Alternately, the workload input to the detailed simulation could be modified, allowing due dates on the lowest priority jobs to slip, and the process repeated as above. Having presented both the aggregate and detailed models in general, and having suggested methods of model interaction, let us in the next chapter discuss the experimentation with these models in particular application to an existing destroyer tender.

CHAPTER IV

MODEL EXPERIMENTATION

IV. A. The Experimental Environment

The naval tender machine shop configuration which we shall use is similar to that found on the latest class of destroyer tenders, exemplified by USS PUGET SOUND (AD-38). The "light section" is partitioned into two machine groups: these groups are the conventional lathes (which are candidates for replacement by numerically controlled lathes) and the other lights (which include drill presses, arbor press, and horizontal turret lathe, none of which are candidates for replacement). The "heavy section" is similarly partitioned into two groups: these groups are the plain and universal mills (which are candidates for replacement by numerically controlled machining centers) and the other heavies (which include engine lathe, vertical turret lathe, vertical mill, drill presses, radial drill press, horizontal boring mill, and gap lathe, none of which are candidates for replacement). In the aggregate model, then, there are four $(I = 4)$ machine groups as follows:

- -- conventional lathes, $(i = 1)$;
- -- mills, $(i = 2)$;
- -- other lights, $(i = 3)$; and
- -- other heavies, $(i = 4)$.

The detailed model, using disaggregated workload data, permits disaggregation of the other lights and other heavies into their actual machinery components; since these machines are rather specialized, it is accepted that their utilization will be somewhat lower than the much more frequently and heavily used lathes and mills.

The workforce is divided into four $(L = 4)$ skill classes as follows:

-- machinery repairman first class, (l = 1);

-- machinery repairman second class, (l = 2);

-- machinery repairman third class, (l = 3); and

-- machinery repairman fireman, (l = 4).

It is assumed that any worker can work on any machine within the shop (this assumption discussed more fully in an earlier chapter); further, there is downward substitution, whereby an idle worker of a higher rating and salary (corresponding to a lower index l) can accomplish work requiring a lesser skilled worker.

The basic planning period of the shop is expressed in hours; therefore the detailed model time parameter of interest will be one hour. Since overseas deployments last at least six months, the aggregate time period parameter will be one month and therefore T = 6. There is no explicit provision for overtime in the aggregate model; but in accordance with the proposed solution scheme, shop performance and manpower utilization are to be determined in the detailed model, and serve as measures of effectiveness for evaluation, and possible iteration with the aggregate model.

IV. B. Generation of Workload

During the field study on board USS PUGET SOUND (AD-38), the historical workload over several months was examined, and that for the month of May 1973 was chosen as typical. Several days were spent with the leading petty officers of both the light and heavy sections; each job was analyzed in detail regarding work accomplished and problems encountered, and the following data were collected for each job:

-- description (whereas the job order may say "repair pump", in fact a new pump shaft may have to be manufactured from raw round stock);

-- skill class required;

-- machine(s) required;

-- prescribed sequence of operations

-- time distributions of each node in the sequence, to determine favorable, most likely, and pessimistic estimates, to include set-up times;

-- job release date to shop;

-- job due date from shop;

-- lot-size or number of items to be manufactured; and

-- job priority as assigned by the customer ship.

These jobs (approximately 178) comprised the workload for the first month (t = 1). For the other five months, various perturbations about this benchmark month were permitted; changes in terms of both skill class and machine group requirements were accomplished.

Once these data were determined, the field study was continued at the Naval Air Rework Facility, Quonset Point, Rhode Island. Each job from the month of May 1973 was explained in detail by a leading petty officer from USS PUGET SOUND, to one or more numerical control machine specialists; for those jobs (or portions of jobs) which could readily be accomplished on numerical control lathes or machining centers, data similar to that above for the conventional machinery accomplishment of the jobs was gathered. It was assumed that the same skill class worker would accomplish the job on either conventional or numerical control machinery. It was found that for approximately half of the jobs (representing approximately half of the required conventional man-hours), numerical control machinery could be utilized with decreases in required time from twenty to over ninety percent for various jobs.

A comparison with the method used by James J. Childs Associates in the previously cited LMI study [22] may be interesting at this point. Childs

and associates studies a sample of fifteen parts in various stages of machining during a study on board USS PUGET SOUND; since several of the fifteen parts could have been worked/manufactured on numerical control machines, they conclude that NC machines "would be generally suitable for use aboard destroyer tenders." Two objections are immediately obvious:

-- the sample size of fifteen was justified by Childs because experience with similar shops in industry had shown such a sample size to be reliable, whereas in fact a tender machine shop cannot pick and choose only that workload which is amenable to numerical control application, so must be concerned with the total amount of work; and

-- although calculation of an economic pay-back period or other common economic measures may be difficult, some examination of cost vs benefit is necessary to justify the new expenditure of funds for numerical control machines.

It was for these reasons that this thesis examined a much larger sample of jobs.

The conventional workload as determined earlier in this section we shall denote as d_{lit}, i.e. demand (in man-hours or machine-hours) for a worker of skill class l on a machine in group i during aggregate period t. This demand serves as the input to the aggregate model. In order to test the sensitivity of the model to changes in aggregate demand, the following demands were utilized:

-- $1.00d_{lit}$, as described above, with 50 percent of the conventional man-and machine-hours in machine groups 1 and 2 capable of being accomplished on numerical control machinery;

-- $1.10d_{lit}$, with the same 50 percent restriction; and

-- $1.20d_{lit}$, with the same 50 percent restriction.

The results of these exercises of the aggregate model will be presented in Chapter V, subsequent to the determination of the several parameters and constants. It will be recalled that the output of these various computer

runs is a recommended manpower and machinery (both conventional and numerical control) configuration; as will be seen, the machinery configuration is not very sensitive, even to a twenty percent increase in workload, and along with a manpower mix will serve as input to the machinery and manpower pools from which the operating elements in the detailed model draw their resources.

The workload which is utilized in the detailed model is simply that for the typical month of May 1973. Using the recommended manpower and machinery configuration from the aggregate model, the detailed model will test the performance of the given configuration on the May 1973 workload data.

IV. C. Determination of Costs, Parameters, and Constants

As discussed in the first chapter, an approach following Anthony [1] would require a hierarchical model composed of three submodels:

-- a strategic planning submodel, dealing with the multi-year decisions;

-- a management control or tactical planning model which would address the efficient and effective utilization of resources, considering an aggregate time period, say from one to six months; and

-- an operational control submodel which would address the daily or hourly operation of the tender machine shop.

Due to the particular constraints inherently introduced to reflect the naval tender structural and contextual environment, however, we have been able to compress the three-level hierarchical model into a two-level model. These particular constraints are as follows:

-- placing aboard any machinery required at any period between overhauls, at the start of the present period [note that Anthony's strategic planning submodel would examine at what point in the between-overhaul cycle would be optimal for placing the machinery aboard]; and

-- manpower of a skill class l needed at any time during the six-month tactical planning horizon are ordered aboard at the start of the deployment and kept on board throughout the deployment.

To determine a value of C_{lt}, the composite standard military pay rate (salary and benefits equivalent) charged for a worker of skill class l in time period t, a Navy Composite Standard Military Rate Table [10] was utilized. The various costs were obtained by dividing the annual rate specified therein by 2, in order to reflect assignment on board for a six-month period. These costs for a six-month period, i.e. $\sum_{t=1}^{6} C_{lt} = C_l$, are as follows:

-- C_1 = \$5060, (l=1);

-- C_2 = \$4130, (l=2);

-- C_3 = \$3566, (l=3); and

-- C_4 = \$3127, (l=4).

To determine a value of C^*_{it}, that share of the acquisition, installation, and incremental operation, maintenance, and overhead costs attendant to bringing aboard a numerically controlled machine into group i, attributable to time t, the following procedure was utilized. The acquisition and installation cost estimates were obtained from the Naval Ship Research and Development Center in Carderock, Md.; an annual incremental expense of \$1000 was assumed for each machine; a salvage value at the end of four years was assumed to be one-half of the initial acquisition and installation cost; these costs were determined over the four-year between-overhaul period, and were equally apportioned throughout each six-month period, after the application of the standard net-present-value method from financial management[32]:

$$C_i^* = \frac{1}{8}\,NPV_i = \frac{1}{8}\left\{\sum_{T=0}^{4}\left[\frac{CF_T}{(1+k)^T}\right]\right\}$$

where NPV_i is the net present value (cost) for machine group i over the four year period,

CF_T is the net cash flow in year T,

k is the discount factor, and

T is time (in years),

for implementing a decision to bring aboard a numerically controlled machine of group i.

The machine cost coefficients for a six month period, i e. $\sum_{t=1}^{6} C^*_{it}=C_i^*$ are as follows:

-- $C_i^*=\frac{1}{8}[68000+1000(0.909+0.826+0.751+0.683)-34000(0.683)]$

$C_i^*=\$5993.375$, (i=1, i.e. NC lathe); and

-- $C_2^*=\frac{1}{8}[110000+1000(0.909+0.826+0.751+0.683)-55000(0.683)]$

$C_2^*=\$9450.50$, (i=2, i.e. NC machining center);

when an assumed value of the discount factor k is 0.10. Since at this point there are no candidates for NC replacement within machine groups 3(i=3) and 4(i=4), determination of a similar cost coefficient is meaningless; the aggregate model structure does, however, allow for later consideration of other candidate groups. An additional comment is necessary regarding the use of a salvage value. Present government budget planners may object to utilization of this concept, since once the money is expended and the equipment purchased, the equipment would most probably be sold at surplus rates much less than the assumed salvage value. An alternative approach is suggested, however: if for some reason numerically controlled machines were determined not to be desirable to remain on board a tender, these machines could be removed and shipped to one of several Naval Air Rework Facilities or naval shipyards for use over a period of several years -- therefore, they would indeed have a "salvage value" at the end of four years.

The third cost component in the objective function is unity (i.e., \$1), such that removal of more conventional machines than necessary to satisfy all of the constraints is discouraged.

The remaining costs and parameters have been defined in detail in the third chapter; therefore, only abbreviated definitions will be utilized below.

The productivity factors, f_i, were initially set at 3 for machine groups 1 and 2, to reflect the increased throughput rates for jobs accomplished on numerically controlled machines in these groups; and the productivity factors were set at 0 for machine groups 3 and 4. A second set of runs, with f_i set at 5, was also accomplished.

The demand, d_{lit}, in conventional hours, representing the workload in May 1973 is as follows (month 1):

-- skill class 1 (l=1) demand on machine groups

	group 1	group 2	group 3	group 4
d_{1i1} =	0	0	0	70

-- skill class 2 (l=2) demand on machine groups

	group 1	group 2	group 3	group 4
d_{2i1} =	53	116	4	35

-- skill class 3 (l=3) demand on machine groups

	group 1	group 2	group 3	group 4
d_{3i1} =	523	118	7	98

-- skill class 4 (l=4) demand on machine groups

	group 1	group 2	group 3	group 4
d_{4i1} =	673	110	50	173

For the demands for the other five months, the reader is referred to appendix B.

The number of hours during a month which a machine must be available for the accomplishment of productive work, h_{it} and h^*_{it}, was set at

$$\left(4\,\frac{\text{week}}{\text{month}}\right)\left(35\,\frac{\text{hours}}{\text{week}}\right) = 140\,\frac{\text{hours}}{\text{month}},$$

for all groups. Since the basic work week for the shop is 35 hours, when the shop is fully manned, there should be machines available, preventing the shop from being machine-limited. Note that setting this parameter at 70 hours per week, and therefore 280 hours

per month, would require 2-shift work in order to have "full employment".

The proportionality constant, k_i, relating the minimum amount of work which must be accomplished on conventional machinery was set as follows:

$k_1 = 0.5$;

$k_2 = 0.5$;

$k_3 = 1.0$; and

$k_4 = 1.0$,

for all runs.

Any increases in workload were shared equally between the conventional and numerically controlled machinery.

The original number of machines in machine group i, b_i, was taken from the existing machine configuration aboard USS PUGET SOUND for groups 1 and 2: $b_1 = 9$ and $b_2 = 5$. For the other machine groups, for which no substitution occurs, large numbers were chosen.

The deck areas for the conventional machines in groups 1 and 2 were taken from the LMI report [22]. The deck areas for candidate numerical control machines in groups 1 and 2 were obtained from the Naval Ship Research and Development Center, Carderock, Md. Since there is no substitution in groups 3 and 4, the deck areas in these groups were set equal to zero; the aggregate model structure does allow for later consideration of substitution within these groups, however. Therefore, the deck areas for this model are as follows:

$A_1 = 96$	sqft	$A_1^* = 105$	sqft
$A_2 = 225$		$A_2^* = 225$	
$A_3 = 0$		$A_3^* = 0$	
$A_4 = 0$		$A_4^* = 0$	

For this model, the factor k', used to introduce more (or less) free deck space, was set at unity.

Although the model structure provides for a constraint considering weights, these rows were not actually used in obtaining the computer results for two reasons:

-- the questions regarding extra foundations for the numerical control machines has not been completely answered, so accurate determination of weights is difficult; and

-- the weight margin m is not sufficiently constraining in present tender design.

The number of man-hours that a worker of skill class l must be available for productive work, h_{lt} and h^*_{lt}, were obtained as follows:

-- $h_{1t} = \left(10 \frac{\text{hours}}{\text{week}}\right)\left(4 \frac{\text{weeks}}{\text{month}}\right) = 40 \frac{\text{hours}}{\text{month}}$, $(l=1)$;

-- $h_{2t} = \left(30 \frac{\text{hours}}{\text{week}}\right)\left(4 \frac{\text{weeks}}{\text{month}}\right) = 120 \frac{\text{hours}}{\text{month}}$, $(l=2)$;

-- $h_{3t} = \left(35 \frac{\text{hours}}{\text{week}}\right)\left(4 \frac{\text{weeks}}{\text{month}}\right) = 140 \frac{\text{hours}}{\text{month}}$, $(l=3)$; and

-- $h_{4t} = \left(35 \frac{\text{hours}}{\text{week}}\right)\left(4 \frac{\text{weeks}}{\text{month}}\right) = 140 \frac{\text{hours}}{\text{month}}$, $(l=4)$.

The figures of allowable productive hours work per week by the first and second class petty officers (l=1, l=2) were chosen arbitrarily to permit their participation in various shop administration, supervision, and training functions. Since the basic shop work-week for planning purposes is 35 hours, this figure was chosen for the lower rated personnel.

CHAPTER V
RESULTS AND CONCLUSIONS

V.A. Results of Model Experimentation

A number of criteria may be used in the evaluation of proposed sets of manpower and machinery configurations. The principal measure of effectiveness used in this study is the total manpower and machinery acquisition cost associated with a particular manpower/machinery configuration for the length of a typical naval tender deployment -- six months. This measure of effectiveness is easily understood and readily accepted; additionally, it is the primary parameter of interest to the Navy decision-maker confronted with the decision of whether to incorporate numerically controlled machinery in tenders and repair ships -- since nearly half of every Defense dollar is spent on personnel items, any scheme which can effectively reduce the required manpower is worthy of consideration. In addition to total cost, a number of measures of effectiveness commonly used in the detailed performance evaluation (e.g., mean flow time, number of jobs completed, manpower and machinery utilization) are reported.

The results of experimentation with the aggregate model are presented in Appendix C . It is interesting to note that in the trial cases when the productivity factors are 3.0 and 5.0, for the $1.00d_{lit}$ and $1.10d_{lit}$ cases, the purchase of numerically controlled machining centers is not recommended; only when the demand is increased by twenty percent of the base case, is purchase of a numerically controlled machining center recommended. Additionally, an interesting solution results regarding numerically controlled lathes: in the f_1=3.0 case, utilization of two N/C lathes is recommended,

whereas for the f_1=5.0 case, only one N/C lathe is reccmmended. Upon first examination, this latter result may appear counterintuitive -- if the machines are more efficient, it may be reasoned, more of them should be brought aboard; alternately, however, since the machines are more efficient (f_1=5.0 vs f_1=3.0), and since the fractions of the total work which can be accomplished on them is constrained, only one N/C lathe is required to accomplish its share of the workload.

With respect to the manpower/machinery costs shown in the aggregate model results, direct comparison between the 1.00d_{lit} (f_i=3.0 and f_i=5.0) cases and a 1.00d_{lit}(f_i=0, i.e. numerically controlled machinery not placed aboard) case is possible. When f_i=0, the required manpower can be obtained by dividing the total conventional workload for skill class 1 by the available number of hours h_{lt} for the appropriate skill class; since no numerically controlled machines are brought aboard, there is no acquisition cost, and therefore no one dollar penalty cost for removing existing machinery. Then, the required manpower would be 3 skill class 1, 3 skill class 2, 7 skill class 3, and 9 skill class 4 personnel, for a total cost of $80675. Comparison of this cost figure with the two earlier cited cases shows that, in the aggregate, the incorporation of numerically controlled machine technology can indeed result in manpower reductions and a lesser total cost.

In order to obtain a greater correlation between the aggregate and the detailed model results, one refinement was utilized in the aggregate model. The data to be input to the detailed model was examined and the productivity factor f_i was modified to reflect differences in productivity not only along machine group lines, but also along skill class lines; the resulting factor,

f_{1i}, relates the productivity of a numerically controlled machine in group i to a conventional machine in group i, for a skill class 1 worker -- f_{1i} can be seen to represent a productivity matrix for both machine groups and skill classes. The result of the aggregate model, with this refinement, for the $1.00d_{lit}$ case is reported in Appendix

Experimentation with the aggregate model sets the number of workers of each skill class and the number of machines of each machine group that will be available during the aggregate time period. These decisions have been made such that the aggregate demand has been met, as well as several other constraints as previously described. However, the aggregate model has not considered such effects as the arrival pattern of jobs, which can severely congest the tender machine shop; additionally, the aggregate model does not address lower level decisions, such as permissible queue lengths for the preferred path before a job will be routed to an alternate, less preferred path. Using the manpower and machinery configuration recommended by the aggregate model, the detailed simulation tests what would actually occur on an hour-by-hour basis. The outputs of the detailed simulation reflect the performance of the configuration recommended by the aggregate model -- measures of effectiveness presented here include the number of jobs completed, mean flow times of completed jobs, and manpower and machinery utilization.

Appendix D lists the jobs input to the detailed model; included are path descriptions and time histograms utilized as input. It is to be noted that the jobs are arranged by job arrival date; for these simulation runs, random arrivals were not allowed -- rather, an identical set of jobs was

utilized. The first simulation utilized that manpower/machinery configuration determined by the aggregate model: 6 conventional lathes, 5 conventional milling machines, 1 numerically controlled lathe, 0 numerically controlled machining centers, the existing configuration of "other lights and heavies", 3 workers of skill class 1, 2 workers of skill class 2, 3 workers of skill class 3 and 9 workers of skill class 4.

The simulation run with the above configuration showed that 34 jobs (of 178 jobs total) were not accomplished; the average elapsed time to accomplish a job (including delays) was 25 hours and 55 minutes, and the average delay for a job was 9 hours and 38 minutes. The utilization data for the various manpower levels indicated that the eighth and ninth members of skill class 4 were needed only 11.2 percent of the time; however, all three of the skill class 3 workers were needed 88.4 percent of the time. The other manpower and machinery utilization appeared to be satisfactory.

Evaluation of the performance data indicated an unsatisfactory job completion rate, probably caused by the number of skill class 3 workers; and since the marginal utilization of the eighth and ninth skill class 4 workers seemed low, this capacity was reduced to seven skill class 4 workers. A second simulation, with skill class 3 augmented by one worker and skill class 4 reduced by two workers(all other manpower and machinery pools unchanged), was accomplished. For this case, 20 jobs were not accomplished; although the average elapsed time to accomplish a job (including delays) increased slightly to 27 hours and 41 minutes, the average delay time for a job was reduced to 8 hours and 36 minutes, indicating that more jobs which required increased machining time were actually completed. The manpower

utilization data shifted such that all 7 members of skill class 4 were needed 20 percent of the time, while all 4 members of skill class 3 were needed 67.1 percent of the time.

In order to obtain a bound to the search for a solution, the next simulation run employed unconstrained machinery and manpower resource pools. The significant increase indicated was an increase in the capacity of the skill class 3 labor pool by an additional worker, to a total of 5 men; the remaining results of the unconstrained run indicated that the manpower and machinery capacities used in the second simulation were satisfactory. Therefore, a run with 5 skill class 3 workers (the other limits unchanged) was accomplished. Marked improvement in the machine shop performance resulted: only 4 jobs were not accomplished; the average elapsed time (including delay) was relatively unchanged to 27 hours and 50 minutes, while the average delay was significantly reduced to 6 hours and 42 minutes. The utilization data for machines and manpower groups of interest are presented, for this last simulation, in Appendix G. Utilization data for manpower skill class 1 is not presented because this skill class was assigned only 2 jobs; although 3 members of this skill class were indicated (since h_{1t}=10 hour/week), only 1 member (at 35 hours/week availability) was utilized in the simulation. Additionally, utilization data for conventional milling machines is not reported: the aggregate model indicated that 5 milling machines were required (since they did not need to be removed), while the maximum simultaneous usage for these machines in the simulation was 3.

There are several comparisons which can be made regarding the solutions generated by the aggregate and the detailed models. The six conventional

lathes recommended were utilized simultaneously in the detailed simulation 62.9 percent of the time, whereas the aggregate model indicated 4.464 were needed; the higher utilization in the simulation reflects the congestion which occurs in the machine shop, which the aggregate model neglects to consider. The aggregate model indicates that 1.0 numerically controlled lathe is necessary to handle the workload; due to the random nature of job arrivals, however, there could exist a sizable queue waiting for a numerically controlled lathe while conventional lathes and their operators stood idly by -- the simulation uses a queue discipline whereby a job can be sent down a secondary path if the queue for the preferred path is too long, and therefore the utilization of the numerically controlled lathe is significantly less than that indicated by the aggregate model solution. Since the principal changes were in manpower groups 3 and 4, and the impact of these on the machine shop performance was presented earlier in this section, they will not be reviewed further.

V. B. Conclusions

A number of conclusions can be drawn from the model experimentation performed in this study. A principal conclusion is that numerically controlled machine tools should be further considered for application to the naval tender machine shop: the aggregate model has shown that, in the aggregate, considerable reductions in manpower cost can be achieved by the incorporation of numerically controlled machine tools aboard naval tenders and repair ships; and the detailed simulation has shown that a numerically controlled lathe would be significantly used to accomplish the assigned workload.

The hierarchical approach whereby the problem is partitioned into two

parts is important, especially from an implementation standpoint. A parameter of critical interest to the Navy decision-maker is the cost of the recommended solution: the aggregate model yields an optimal solution (i.e., minimum total cost) and provides a good starting set of parameters with which to enter the simulation. Then, depending on the effects of congestion and the decision-maker's desire to improve the system performance, the capacity pools in the simulation can be modified; but throughout the process of changing manpower and machinery capacities in the simulation, the decision-maker has a benchmark for comparison -- the aggregate model solution. If only a simulation were used, without the benefit of the aggregate model, the solution would be highly dependent on the ingenuity of the decision-maker in picking which step to take next; although another pool (containing dollars) could be established, there would be no assurance that a nearly optimal solution would exist at any point in the simulation process. Additionally, the nature of the costs involved is given explicit recognition in the aggregate model; treatment of these costs from only a day-to-day perspective could result in the neglect of a very important component in the solution.

The manpower and machinery configurations suggested by the model experimentation described are as follows: a) remove two conventional lathes, and replace them with one numerically controlled lathe; b) do not replace any of the existing conventional milling machines with numerically controlled machining centers; and c) if the manpower available to the tender machine shop is available to work, on the average, the number of hours h_{1t} as described in

Chapter IV, then assign three machinery repairmen first class, two machinery repairmen second class, five machinery repairmen third class, and seven machinery repairmen "strikers" (a skill class 4 worker in the model formulation).

In the implementation of this work, there are a number of important issues which must be further examined. Since a major input to both the aggregate and detailed models is the demand faced by the naval tender machine shop, effort should be expended to determine what this demand really is; the demand from one month (which was represented as typical at the time the data was gathered) was used in this study, but it may be desirable to simulate an entire deployment period rather than one month chosen at random. Machinery breakdown and maintenance times were not included, but could be easily input on a probabilistic basis. The time availability for the various skill classes was selected with various assumptions: the skill classes were trained to appropriate levels (rather than having capable personnel transferred, and replaced with less skilled personnel); the skill classes were not required to leave the machine shop to perform other work (e.g., loading of stores); and hospitalization and leave time were not included.

A number of extensions to the proposed model are possible. Among those which would more closely approximate the actual environment of the naval tender machine shop are the following:

-- utilization of "duty" personnel on second and third shifts;

-- utilization of overtime on weekends;

-- rework of jobs which do not meet specifications; and

-- recognition of job priority in the assignment section of the detailed simulation.

In this thesis, a hierarchical approach for determination of manpower and machinery allocations in a naval tender machine shop has been presented. It was determined that numerically controlled machinery can indeed reduce the manning level in the shop; or alternately, the present on-board manpower can significantly increase the output of the shop under conditions of increased demand, given that numerically controlled machine technology is applied to the naval tender machine shop.

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Appendix A: Aggregate Model Computer Program (MPSX-MIP)

```
PROGRAM
INITIALZ
MOVE (XDATA,"NCCONTRL')
MOVE(XPBNAME, 'PBFILE')
CONVERT ('SUMMARY')
BCDOUT
SETUP ('BOUND', 'TOOHI')
MOVE (XOBJ, 'VALUE')
MOVE (XRHS,'RIGHTON')
CRASH
PRIMAL
SOLUTION
OPTIMIX ('COST', 0.0.,0,0)
RANGE
EXIT
PEND
```

Rows	Sign	Constraint Number
1-96	E	(1)
97-120	E	(2)
121-132	E	(3)
133-156	L	(4)
157-168	L	(5)
169-192	G	(6)
193-196	L	(7)
197-198	G	(8)
199-200	L	(9)
201-224	E	(10)
225-248	E	(11)
249-272	E	(12)
273-296	L	(13)

where E ≡ equal to
L ≡ less than
G ≡ greater than

Appendix B: Workload Data Input to Aggregate Model, d_{lit}, for the $1.0d_{lit}$ case

d_{lit} = number of conventional hours workload demand on machine group i to be performed by skill class l in aggregate time period t

Aggregate time period t = 1

	i = 1	i = 2	i = 3	i = 4	Σ
l=1	0	0	0	70	70
l=2	53	116	4	35	208
l=3	523	118	7	98	746
l=4	673	110	50	173	1006
Σ	1249	344	61	376	2030

Aggregate time period t = 2

	i = 1	i = 2	i = 3	i = 4	Σ
l=1	0	35	0	70	105
l=2	60	110	20	35	225
l=3	560	120	0	100	780
l=4	660	120	60	190	1030
Σ	1280	385	80	395	2140

Aggregate time period t = 3

	i = 1	i = 2	i = 3	i = 4	Σ
l=1	16	16	0	50	82
l=2	45	110	10	40	205
l=3	520	120	30	120	790
l=4	700	100	90	150	1040
Σ	1281	346	130	360	2117

Aggregate time period t = 4

	i = 1	i = 2	i = 3	i = 4	$\sum$
l=1	40	10	0	60	110
l=2	93	110	30	70	303
l=3	600	112	20	115	847
l=4	625	100	65	200	990
$\sum$	1358	332	115	445	2250

Aggregate time period t = 5

	i = 1	i = 2	i = 3	i = 4	$\sum$
l=1	0	0	0	50	50
l=2	65	146	10	0	221
l=3	500	90	0	120	710
l=4	600	125	65	175	965
$\sum$	1165	361	75	345	1946

Aggregate time period t = 6

	i = 1	i = 2	i = 3	i = 4	$\sum$
l=1	0	0	0	75	75
l=2	75	155	35	16	281
l=3	625	140	0	128	893
l=4	746	134	122	213	1215
$\sum$	1446	429	157	432	2464

Appendix C : Aggregate Model Results

N_{it} = the number of conventional machine tools in machine group i required during aggregate time period t

N_{it}^* = the number of numerically controlled machine tools in machine group i required during aggregate time period t

M_{lt} = the number of workers of skill class l required during time period t

f_i = productivity factor, relating ratio of productivities of a numerically controlled machine in group i to a conventional machine in group i

f_{li} = productivity factor, utilized on second iteration, relating the productivity factor of a numerically controlled machine in group i to a conventional machine in group i, for a skill class l worker

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	Integer Solution	Overall Utilization
N_1	4.464	6.00	4.571	4.850	4.164	5.164	6	0.811
N_2	2.457	2.750	2.471	2.371	2.578	3.064	4	0.654
N_1*	1.843	1.048	1.526	1.617	1.886	1.828	2	0.812
N_2*	0	0	0	0	0	0	0	-

	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	Integer Solution	Overall Utilization
M_1	3.00	2.625	3.00	2.083	3.00	3.00	3	0.928
M_2	1.439	1.542	1.458	2.008	1.480	2.432	3	0.575
M_3	4.00	4.00	4.00	3.450	4.00	3.402	4	0.952
M_4	5.795	7.119	6.309	7.071	6.812	7.997	8	0.856

Total Cost = $78838

Aggregate model results for 1.00d_{1it}, f_i=3.0,case

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	Integer Solution	Overall Utilization
N_1	4.914	6.00	5.034	5.329	4.586	5.686	6	0.876
N_2	2.707	3.029	2.721	2.600	2.836	3.371	4	0.719
N_1*	1.938	1.352	1.679	1.783	1.988	1.895	2	0.886
N_2*	0	0	0	0	0	0	0	-

	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	Integer Solution	Overall Utilization
M_1	3.00	2.900	3.00	2.292	3.00	2.075	3	0.904
M_2	1.586	1.700	1.606	2.211	1.625	2.592	3	0.629
M_3	4.00	3.738	4.00	3.776	4.00	3.774	4	0.970
M_4	6.793	8.093	7.345	7.785	7.507	9.00	9	0.862

Total Cost = $81966

Aggregate model results for $1.10d_{1it}$, f_i=3.0 ,case

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	Integer Solution	Overall Utilization
N_1	5.357	5.657	5.493	5.829	5.00	6.400	7	0.803
N_2	1.957	1.683	1.521	1.421	1.543	1.836	2	0.830
N_1*	1.790	1.774	1.829	1.938	1.662	2.00	2	0.916
N_2*	0.331	0.552	0.481	0.521	0.945	0.686	1	0.586

	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	Integer Solution	Overall Utilization
M_1	2.100	2.450	3.00	3.00	3.00	3.00	3	0.919
M_2	0.956	1.850	1.428	1.678	1.403	2.00	2	0.517
M_3	3.407	3.269	4.00	3.729	4.00	3.392	4	0.908
M_4	8.352	8.143	7.690	8.486	7.462	10.00	10	0.836

Total Cost = $90414

Aggregate model results for $1.20d_{1it}$, f_i=3.0,case

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	Integer Solution	Overall Utilization
N_1	4.464	6.00	4.571	4.937	4.164	5.739	6	0.830
N_2	2.814	2.750	2.471	2.371	2.578	3.064	4	0.669
N_1*	0.891	0.886	0.916	0.952	1.00	0.917	1	0.927
N_2*	0	0	0	0	0	0	0	-

	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	Integer Solution	Overall Utilization
M_1	3.00	2.625	2.050	1.950	1.840	1.875	3	0.741
M_2	1.380	1.475	1.408	1.905	1.408	2.00	2	0.798
M_3	2.340	2.371	2.671	3.00	2.214	3.00	3	0.856
M_4	6.911	8.643	6.994	7.071	6.795	8.679	9	0.835

Total Cost = $68276

Aggregate model results for $1.00d_{1it}$, f_i=5.0,case

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	Integer Solution	Overall Utilization
N_1	5.286	5.186	5.500	6.325	4.586	6.916	8	0.704
N_2	2.707	3.029	2.721	2.600	2.836	3.371	4	0.719
N_1*	0.904	0.974	0.914	0.870	0.914	0.891	1	0.911
N_2*	0	0	0	0	0	0	0	-

	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	Integer Solution	Overall Utilization
M_1	1.925	2.900	3.00	2.145	1.375	2.075	3	0.745
M_2	1.522	1.627	1.550	2.097	1.545	2.592	3	0.607
M_3	2.586	2.609	2.939	4.00	2.436	4.00	4	0.774
M_4	7.907	8.093	8.171	7.786	7.490	9.00	9	0.903

Total Cost = $75972

Aggregate model results for $1.10d_{1it}$, f_i=5.0, case

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	Integer Solution	Overall Utilization
N_1	5.771	6.171	5.979	6.643	5.143	7.779	8	0.781
N_2	1.514	1.643	1.521	1.421	4.00	1.836	4	0.497
N_1*	0.991	0.961	1.00	1.00	0.969	0.924	1	0.974
N_2*	0.339	0.331	0.288	0.397	0.793	0.506	1	0.442

	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	Integer Solution	Overall Utilization
M_1	3.00	2.310	2.070	3.00	3.00	3.00	3	0.910
M_2	1.657	2.00	1.690	1.580	0.708	1.568	2	0.767
M_3	2.207	3.00	3.00	3.00	3.00	3.00	3	0.956
M_4	7.874	8.005	7.948	9.050	11.00	10.885	11	0.830

Total Cost = $83981

Aggregate model results for $1.20d_{1it}$, f_i=5.0, case

	N_{i1}	N_{i2}	N_{i3}	N_{i4}	N_{i5}	N_{i6}	Integer Solution	Overall Utilization
N_1	4.464	4.571	4.571	4.850	4.286	5.729	6	0.790
N_2	2.457	2.750	2.471	2.371	2.578	3.064	5	0.523
N_1^*	1.00	0.895	0.891	0.972	1.00	0.928	1	0.947
N_2^*	0	0	0	0	0	0	0	-

	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	Integer Solution	Overall Utilization
M_1	2.140	2.625	2.050	2.750	1.889	1.875	3	0.740
M_2	1.389	1.875	1.417	1.922	1.420	2.00	2	0.835
M_3	2.340	2.371	3.00	3.00	2.214	3.00	3	0.885
M_4	6.90	6.880	6.634	6.76	6.893	8.679	9	0.792

Total Cost = \$68276

Aggregate model results for $1.00d_{1it}, f_{1i}$ matrix (shown below) case

$$f_{1i} = \begin{array}{c|cccc} i \backslash 1 & 1 & 2 & 3 & 4 \\ \hline 1 & 0 & 4.5 & 5 & 6 \\ 2 & 0 & 8 & 2.5 & 3 \end{array}$$

Appendix D: Listing of Jobs Input to the Detailed Model

Arrival Date	Priority	Labor Class	Preferred Path	Time Tables 1	Time Tables 2	Alternate Path	Time Tables 1	Time Tables 2
0	4	4	C	F	A	K	H	H
	5	3	B	L	H			
	5	3	B	L	H			
	5	3	B	L	H			
	9	4	D	A	-	A	H	-
	3	3	B	F	G			
	4	4	A	K	-			
	4	2	A	G	-			
	7	2	C	A	C	B	G	E
	8	4	A	I	-			
	4	4	D	G	-	A	M	-
	2	4	D	A	-	B	G	B
	4	4	T	H	B			
	2	3	D	C	-	A	A	-
	4	4	A	G	-			
	4	4	N	E	-			
	5	3	A	J	-			
	4	4	A	B	-			
1	3	4	A	C	-			
	6	3	H	J	C			
	5	4	A	D	-			
	5	4	A	C	-			
	1	4	X	K	-			
	1	4	A	E	-			
	8	2	M	D	I			
	5	4	Y	F	-	U	A	S
	7	4	A	G	-			
2	9	4	A	D	-			
	6	3	I	A	E	H	D	E
	5	2	B	K	K			
	1	3	A	G	-			
	7	4	A	K	-			
3	9	3	E	F	A	B	M	I
	9	4	C	A	A	B	E	B
	9	3	Y	H	-	B	P	E
	9	3	D	F	-	A	F	-
	4	3	D	A	-	A	D	-
	9	4	F	B	C	B	N	C
	7	2	C	A	C	B	G	E
	7	2	B	A	M			

Arrival Date	Priority	Labor Class	Preferred Path	Time Tables 1	2	Alternate Path	Time Tables 1	2
4	8	4	D	A	-	A	C	-
	9	4	D	H	-	Q	L	-
	2	4	A	J	-			
	7	4	A	C	-			
	8	4	P	L	-			
	8	4	R	C	-			
5	5	4	T	B	B			
	5	4	D	A	-	A	F	-
	5	4	T	C	B			
	2	2	G	E	-			
	7	4	A	A	-			
6	4	2	A	M	-			
	7	4	A	C	-			
7	7	4	D	A	-	A	D	-
	7	4	F	A	C	B	G	C
	9	3	U	E	B			
	5	4	A	H	-			
	8	4	A	B	-			
	9	4	K	B	A			
	7	3	D	A	-	A	G	-
	2	3	A	Q	-			
	5	4	A	D	-			
	6	4	K	B	A			
	9	4	Y	H	-	U	A	T
	4	4	E	C	C	f	C	J
	5	4	D	A	-	A	F	-
	4	3	A	J	-			
	2	4	W	N	H			
	5	4	Z	G	-			
	2	4	F	A	C			
8	7	4	E	A	A	B	I	D
	7	4	H	D	F			
9	8	2	L	K	N			
	7	4	P	D	-			
	5	3	F	A	D	B	D	D
10	2	3	G	D	-			
	2	3	G	D	-			
	3	4	A	G	-			
	7	3	U	G	B			
	8	3	W	F	N			
	6	4	D	A	-	E	B	-

Arrival Date	Priority	Labor Class	Preferred Path	Time Tables ①	Time Tables ②	Alternate Path	Time Tables ①	Time Tables ②
10 (cont)	8	3	A	H	-			
	8	4	A	C	-			
	9	4	A	E	-			
	9	2	D	A	-	A	E	-
	8	4	Z	C	-			
	9	3	Y	C	-	U	A	K
	6	3	H	F	E			
	6	3	H	F	E			
	6	3	H	F	E			
	3	3	B	F	G			
	3	3	A	I	-			
11	2	3	G	D	-			
	9	4	D	B	-	A	H	-
	9	3	B	F	G			
	4	3	D	D	-	B	I	C
13	4	4	F	A	A	B	F	C
	6	4	D	A	-	A	E	-
	4	2	D	A	-	K	E	-
	4	2	T	L				
	4	2	N	C				
	4	1	N	R				
	4	4	A	Q				
	4	4	A	Q				
	4	4	A	T				
	4	4	A	K				
	4	4	D	E	-	A	K	-
14	2	4	A	C	-			
	2	4	A	B	-			
	8	4	E	C	A	A	R	-
	7	2	A	I	-			
	4	3	A	H	-			
	5	3	C	D	E	B	R	K
15	7	4	F	C	C	B	G	C
	3	3	L	F	G			
	5	4	A	C	-			
	4	4	W	B	A			
	7	4	D	E	-	A	K	-
	2	4	H	A	C			
	4	4	D	F	-	A	M	-
	4	4	D	G	-	A	L	-
	4	4	D	F	-	A	K	-

Arrival Date	Priority	Labor Class	Preferred Path	Time Tables ①	Time Tables ②	Alternate Path	Time Tables ①	Time Tables ②
16	2	3	A	E	-			
	7	4	F	A	C	B	L	C
	4	1	N	R	-			
	5	4	R	B	-			
17	8	4	D	A	-	A	G	-
	5	3	A	P	-			
	7	3	A	P	-			
18	7	4	D	A	-	A	C	-
	7	4	D	B	-	A	D	-
	7	4	R	B	-			
	2	3	G	D	-			
	8	4	D	A	-	A	E	-
	4	4	D	A	-	A	E	-
19	8	3	D	C	-	A	M	-
20	4	4	F	F	B	B	M	C
	9	4	H	I	C			
	8	4	R	E	-			
21	4	3	H	P	B			
	4	3	L	J	A			
22	2	3	A	K	-			
	4	3	A	B	-			
	6	3	B	I	D			
	9	4	A	E	-			
	7	4	D	A	-			
	8	2	Z	L	-			
	7	4	A	E	-			
	9	4	A	H	-			
	8	3	A	J	-			
	9	4	R	D	-			
23	9	3	G	D	-			
	7	4	A	C	-			
	7	4	A	C	-			
	8	3	A	M	-			
	8	4	D	A	-	A	D	-
	8	3	A	S	-			
24	9	4	A	H	-			
	7	4	A	G	-			

Arrival Date	Priority	Labor Class	Preferred Path	Time ①	Tables ②	Alternate Path	Time ①	Tables ②
25	7	4	V	C	-			
	8	4	K	D	E			
	7	3	B	Q	Q			
	7	3	W	E	A			
	9	4	R	G	-			
	7	4	B	F	B			
26	7	4	F	A	B	B	F	B
	7	4	A	F	-			
	9	4	R	G	-			
	9	4	R	D	-			
27	1	4	A	E	-			
28	8	4	J	B	B			
	2	3	G	D	-			
29	8	4	D	A	-	A	E	-
	7	4	D	A	-	A	C	-
30	4	4	A	M	-			
	7	4	D	A	-	A	K	-
	8	3	A	G	-			

Appendix E: Time Tables Utilized in Detailed Model, where probability is the cumulative probability

Table	Prob	Time	Prob	Time	Prob	Time	Prob	Time	Prob	Time
A	0.0	0.25	0.25	0.33	0.5	0.5	0.75	0.75	1.0	1.0
B	0.0	0.5	0.25	0.6	0.5	1.0	0.75	1.3	1.0	1.5
C	0.0	1.5	0.25	1.6	0.5	2.0	0.75	2.3	1.0	2.5
D	0.0	2.5	0.25	2.6	0.5	3.0	0.75	3.3	1.0	3.5
E	0.0	3.5	0.25	3.6	0.5	4.0	0.75	4.3	1.0	4.5
F	0.0	4.5	0.25	4.6	0.5	5.0	0.75	5.3	1.0	5.5
G	0.0	5.0	0.25	5.4	0.5	7.0	0.75	8.6	1.0	9.0
H	0.0	6.0	0.25	6.4	0.5	8.0	0.75	9.6	1.0	10.0
I	0.0	7.5	0.25	8.0	0.5	10.0	0.75	12.5	1.0	13.0
J	0.0	9.0	0.25	4.5	0.5	12.0	0.75	15.0	1.0	15.5
K	0.0	11.0	0.25	11.5	0.5	14.0	0.75	17.0	1.0	17.5
L	0.0	13.0	0.25	13.5	0.5	16.0	0.75	19.0	1.0	20.0
M	0.0	18.0	0.25	14.0	0.5	21.0	0.75	23.0	1.0	25.0
N	0.0	23.0	0.25	23.7	0.5	25.0	0.75	26.5	1.0	27.0
P	0.0	26.0	0.25	26.7	0.5	28.0	0.75	30.0	1.0	31.0
Q	0.0	28.2	0.25	28.7	0.5	30.0	0.75	33.5	1.0	35.0
R	0.0	30.0	0.25	31.5	0.5	35.0	0.75	40.0	1.0	42.0
S	0.0	35.0	0.25	36.0	0.5	40.0	0.75	45.0	1.0	49.0
T	0.0	55.0	0.25	56.0	0.5	60.0	0.75	64.0	1.0	65.0

Appendix F : Paths in Simulation Network

Path	Node 1	Node 2	Node 3	Node 4
A	QA1	Conv Lathe		
B	QB1	Conv Lathe	QB2	Conv Mill
C	QC1	NC Mill	QC2	NC Lathe
D	QD1	NC Lathe		
E	QE1	NC Lathe	QE2	NC Mill
F	QF1	NC Lathe	QF2	Conv Mill
G	QG1	Vertical Mill		
H	QH1	Conv Lathe	QH2	Cleerman Drill
I	QI1	NC Lathe	QI2	Cleerman Drill
J	QJ1	Band Saw	QJ2	Conv Lathe
K	QK1	Cleerman Drill	QK2	Conv Lathe
L	QL1	Gap Lathe	QL2	Conv Mill
M	QM1	Monarch Lathe	QM2	Conv Mill
N	QN1	Horiz Bar Mill		
P	QP1	Band Saw		
Q	QQ1	Horiz Tur Lathe		
R	QR1	Radial Drill		
T	QT1	Conv Mill	QT2	Cleerman Drill
U	QU1	Conv Lathe	QU2	Wells Index
V	QV1	Vert Tur Lathe		
W	QW1	Conv Mill	QW2	Vertical Mill
X	QX1	Drill Press		
Y	QY1	NC Mill		
Z	QZ1	Bullard		

Appendix G : Utilization Data for Selected Machinery Types and Manpower Skill Classes, as Determined by the Detailed Model

Conventional Lathes

number	%
0	0
1	0
2	2.6
3	7.3
4	10.4
5	16.8
6	62.9

Numerically Controlled Lathe

number	%
0	61.2
1	38.8

Skill Class 2 Manpower

number	%
0	20.2
1	1.8
2	78.0

Skill Class 3 Manpower

number	%
0	0
1	4.5
2	17.2
3	19.7
4	12.9
5	45.8

Skill Class 4 Manpower

number	%
0	1.4
1	18.3
2	11.5
3	19.0
4	17.1
5	10.3
6	1.6
7	20.6